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Urban transport traffic network regulation and evaluation using a fuzzy evolutionary approach

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Abstract - The real-time traffic regulation of an urban collective transport network is a very hard problem, especially in case of appearance of simultaneous disturbances (vehicle's breakdown, strike, and demonstration....etc). Indeed, regulator (decision-maker) has to carry out difficult tasks that are often inaccessible at the human scale, which involves the assistance of a decision support system (DSS). In this paper, we present the pit of this DSS which is a generator and an evaluator of the decision strategies for a disrupted traffic transport network regulation. Our evaluation proposed module is based on a hybrid approach using a fuzzy evaluation method and an evolutionary algorithm. It treats the regulation problem as an optimization one and provides the regulator with evaluated and classified effective decisions by taking into account his/her preferences.

Keywords: fuzzy logic, Evolutionary algorithms, decision making, optimization, urban transport network.

I. INTRODUCTION

The hard difficulty related to traffic management of the urban collective transport networks is the respect of the planned departure and arrival times of vehicles at the different stops in the network. In fact, the planning process at the transport company consists at first in establishing different timetables that describe trips according to the lines, the frequencies, the transport demand and the travel times in the network. These trips are then transformed into blocks and assigned to vehicles [1] [11]. A crew scheduling process finally follows this vehicles scheduling. Hence, the vehicle schedules are fixed for every timetable period.

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However, in reality, travel times and transport demand are not fixed because of random external influences that affect the traffic within the network and cause disturbances. These disturbances caused for example by traffic jams; accidents; or strikes; may force customers to wait longer, affect the transit time of customers at the correspondence nodes and thus decrease the level of service.

Consequently, effective operational decisions must be taken in real-time by regulators to reduce the effects of the disturbances, and the theoretical schedules have to be adapted to the real traffic conditions through regulation, or rescheduling tasks[1] [11] [12]. This process is then called reactive scheduling. It results in the creation of new schedules that increase the level of service by undertaking operational decisions, such as, delay one or some vehicles, the injection of an extra vehicle in the network or the deviation of the routes of some vehicles ...etc. Actually, it's a human operator, regulator, who performs these real time tasks and controls the global network traffic by treating the information provided by the Automatic Vehicles Monitoring (AVM) system and the vehicle drivers. However, the regulator is usually overloaded with information, which complicates its decision-making task. Moreover, despite the AVM system assistance, the regulator spends more than 50% of this work time in communication with the vehicle drivers. In order to take efficient decisions, it is necessary:

- to have a global vision about the network;
- to treat immediately the available information about the network state;
- to make a space-time analysis of the disturbances;
- to project in the future the effect of the regulation actions on the network (evaluation and classification)

Moreover, in the real-time regulation process, one is required to optimize several objectives simultaneously (regularity of the time intervals, transfer time, route time, service quality, crossed kilometers etc...) under various constraints, and such problem is formulated as a NP-hard Multiobjective Optimisation Problem (MOP) that is difficult to solve with classical methods [1] [8] [13].

Hence, the regulator has to assure difficult tasks that are often inaccessible at the human scale especially if many disturbances occur simultaneously, which involves the assistance of a decision support system (DSS). The regulator

so needs a tool allowing him/her to estimate the gravity of a disturbance and which can propose him/her effective and estimated decisions according to his/her preferences

In this paper, we present the pit of this decision support system which is a generator and an evaluator of the decision strategies. We propose an interactive and effective approach for the disturbed urban transport network regulation. Especially, we try to assist the regulators to evaluate a pertinence of a disturbance and to choose the most efficient decision. From the detection of disturbances, we determine the space-time horizon corresponding to every one (disrupted zone), then we compare these zones to know if they are independent (empty intersection) or not. After that, we call our generation and evaluation module to build practicable decisions and to evaluate them. Thus, we provide the regulators with evaluated and classified decisions.

The remains of this paper is organised as follows: in the second part we present a new mathematical formulation of the regulation problem. Then a developed evaluator of the decision strategies will be described in the third section. The fourth section focuses on simulation results obtained by using the suggested approach. Finally, the last section deals with the concluding remarks and research perspectives.

II. MATHEMATICAL FORMULATION

2.1 Regulation horizon determination

In order to control the disturbances evolution, it is necessary to define first the disturbance space-time horizon. In other words, we have to search a set of network entities (vehicles and stations) involved in the disturbance to be reduced, what consists, in fact, in establishing the corresponding regulation horizon according to:

- A spatial axis represented by stops included in the disturbance or the regulation
- A temporal axis represented by vehicles included in the disturbance or the regulation.

We illustrate the set of stops considered by S^H and the set of the vehicles by V^H . Then, we represent the space-time regulation horizon by $H = \{S^H \cup V^H\}$. We note the k th station of the line r by s_k^r . We also; represent the i th vehicle of the line l by v_i^l . The decisions of regulation concern then any vehicle $v_i^l \in V^H$ and any station $s_k^r \in S^H$

In [1], authors have, really, supposed that the zone of disturbance left for the timetable on which we act, is given. However, that zone is not available in real situation at the moment of the disturbance. Hence, we propose in this paper a method allowing us the regulation horizon determination.

Let us suppose that we have a meshed network with several lines and we suppose to have the following information concerning the detected disturbance:

- The time of disturbance detection t_{distr} ;

- The line L_{distr} of the network on which occurs disturbance and its frequency f ;
- The disrupted vehicle V_{distr} ;
- The station where disturbance was detected or where the disrupted vehicle makes its first stop after the disturbance detection noted S_{distr} ;
- Delay r of the vehicle V_{distr} at the station S_{distr}
- The disrupted vehicle average speeds before and after the disturbance.

A first stage will consist so in determining the set of vehicles and stations of the line L_{distr} concerned by the regulation process. So, to make that, we developed a method inspired from an algorithm of regulation in terminus presented in [3]. This algorithm (Fig.1) starts when a vehicle arrives at the terminus with a delay exceeding its beating time (pause in the terminus before the resumption of the service). It operates by delaying vehicles following the disrupted vehicle during their passage in the terminus, in order to keep the time intervals as regular as possible. The regulator has to supply hoped hour for the return at the theoretical timetable foreseen before the disturbance, so the algorithm will determine the number of vehicles which will pass in the terminus before the return in the normal regime, it calculates also, by using a simple geometrical method a delay to be imposed on every vehicle in its passage in the terminus.

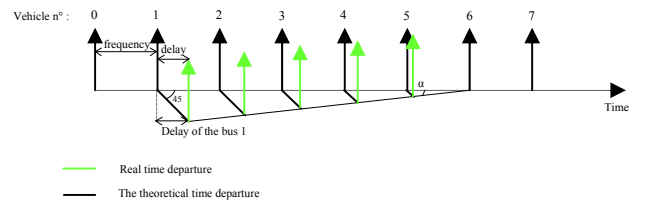


Fig.1. Principle of the regulation in terminus

We noticed that the determination of the number of vehicles to be considered returns in fact in the determination of the angle α and after our analysis of this algorithm we were able to establish a following relation between $\tan(\alpha)$ and the

deceleration of the disrupted vehicle $\frac{V_2}{V_1} < 1$ where V_1 and

V_2 are respectively the average speeds before and after the disturbance.

$$\tan(\alpha) = 1 - \frac{V_2}{V_1} \quad (1)$$

$$\text{But } \frac{V_2}{V_1} = \frac{t_1}{t_2} = \frac{t_1}{t_1 + r} \quad (2)$$

Where t_1 and t_2 are respectively the route durations before and after the disturbance of the disrupted vehicle between the disrupted station and its following station.

From this report, knowing the disrupted vehicle delay and speed before and after the disturbance, we considered the station which discovered disturbance as partial terminus. So, it is easy to calculate the number N_{up} of upstream vehicles by using the formula:

$$\tan(\alpha) = \frac{r}{(f-r) + (n_0-1)f} \quad (3)$$

$$\text{Hence, } n_0 = \frac{r(1 - \tan(\alpha))}{f \tan(\alpha)} \quad (4)$$

where, r is delay of the disrupted vehicle and f is the disrupted line frequency.

$$N_{up} = (E(n_0) + 1) + 1 \quad (5)$$

Where $E(n_0)$ is the integral part of n_0 .

Generally, according to regulators and their experience, we have to act on more vehicles upstream than downstream. Indeed, regulators consider most of the time that the number of downstream vehicles is equal to the upstream vehicles number less one or two, and this is according to the aptness of the disturbance and the line frequency.

We suggest so calculating the number N_{down} of downstream vehicles by using the following formula:

$$N_{down} = \begin{cases} N_{up} - 1, & \text{if } 0 < N_{up} \leq 3 \\ N_{up} - 2, & \text{if } N_{up} > 3 \\ N_{up}, & \text{if not} \end{cases} \quad (6)$$

Finally, the total vehicles number is:

$$N_T = N_{up} + N_{down} + 1 \quad (7)$$

We note S_{up} the first station which the vehicle ($V_{distr} + N_{up}$) is going to serve after the moment of disturbance t_{distr} , and S_{down} the first station which the vehicle ($V_{distr} - N_{down}$) is going to serve after t_{distr} . So all the stations included between S_{up} and S_{down} belong to the zone of disturbance. Thus, we determine the vehicles and stations of the line L_{distr} belonging to the disturbance zone.

The following stage consists in finding among the stations of the line L_{distr} (that belong to the horizon of regulation) those corresponding to the correspondence nodes.

In case a correspondence node is included in the disrupted zone early defined and if a correspondence risks not to take place because of the incident, it is necessary to widen the disrupted zone to the set of vehicles and stations of the line which makes a passengers exchange with the disrupted line.

To determine vehicles and stations of this line that must be included in the disturbance zone, we use the same method; only modification to be made is to replace the disrupted vehicle by that in correspondence with it and the disrupted line frequency by that of the line with it makes passenger exchange (Look at the example of simulation).

Our method has two advantages; the first is to allow us the treatment of two or more simultaneous disturbances, and the second is to reduce the size of the search space.

2.2 Decision variables

The variable of passage, a_{ij}^{lm} associated to the vehicle V_i^l and to the stop s_j^m is equal to 1 if the vehicle V_i^l crosses by this stop and 0 otherwise.

The variable of destination, x_{ijk}^{lmr} is equal to 1 when V_i^l goes directly from s_j^m to s_k^r and to 0 otherwise [1]. We note ta_{ij}^{lm} the arrival time of the vehicle V_i^l at the stop s_j^m and td_{ij}^{lm} its departure time from this stop.

Considering the initial duration, t_{ijk}^{lmr} of the direct route of the vehicle V_i^l between the stations s_j^m and s_k^r , we represent the modification of the route time between these two stops δ_{ijk}^{lmr} .

The variable ε_{ij}^{lm} denotes the supplementary stop time of the vehicle V_i^l at the stop s_j^m .

2.3 Criteria

In this paper we deal with five regulation criteria which summarize the objectives of the project in which joins this work, it is a question of minimizing: the waiting time of the customers, the transfer time of the correspondences and the duration of routes time in the network to improve the comfort of the customers (quality of service). These criteria are the following: regularity, correspondence, punctuality, commercial kilometers and the quality of service.

a) Regularity criterion:

Regularity allows satisfying two objectives: to minimize the customers Waiting Time in stops and to balance loads between vehicles.

Let us now consider that V_i^l , the successor of V_i^l at s_j^m . The time interval between the successive passages at this stop is:

$$\Delta t = ta_{i,j}^{lm} - td_{ij}^{lm} \quad (8)$$

Before calculating the total waiting time, we suppose that for every vehicle V_i^l passing by s_j^m , expression $s_k^r > s_j^m$ represents stops $s_k^r \in S^H$ included in its route after s_j^m .

The expected number of persons arriving at s_j^m travelling to s_k^r is equal to:

$$\text{waiting}(\Delta t, S_j^m) = \int_0^{\Delta t} \mu_{S_j^m}(t) \times (\Delta t - t) dt \quad (9)$$

The total waiting time of the passengers at the different stops of the spatial horizon is formulated as

$$WT = \sum_{S_j^m \in S^H} \sum_{V_i^l \in V^H} a_{ij}^{lm} \left(\sum_{S_k^r > S_j^m} \int_0^{\Delta t} \mu_{S_k^r}^m(t) \times (\Delta t - t) dt \right) \quad (10)$$

with, $\mu_{S_k^r}^m$ is the arriving rate of the passengers travelling between the stations S_j^m and S_k^r

b) Transfer criterion:

The transfer criterion is related to the Transfer Time at the different nodes of the network.

This criterion can be formulated as follows:

$$TT = \sum_{V_i^l \in V^H} \sum_{V_j^l \in V^H} \sum_{S_j^m \in S^H} y_{ii^l}^{ll^m} \times \max(w_{ii^l}^{ll^m} \times Trans, td_{i^l j}^{ll^m} - td_{ij}^{lm}) \quad (11)$$

Here, $y_{ii^l}^{ll^m}$ is the connection variable, it is equal to 1 if a correspondence is possible from the vehicle V_i^l to V_j^l at the station S_j^m and equal to 0 otherwise, $w_{ii^l}^{ll^m}$ is the number of persons in transfer from V_i^l to V_j^l at the station S_j^m and $Trans$ is the correspondence duration per person.

c) Route time criterion:

It consists in minimizing the total duration of routes aboard the various vehicles according to their loads.

By taking in the following expression S_j^m as the previous stop of the vehicle V_i^l for all $V_i^l \in V^H$ and $S_k^r \in S^H$, we calculate the total Route Time, RT.

$$RT = \sum_{V_i^l \in V^H} \sum_{S_j^m \in S^H} a_{ij}^{lm} \times C_{ij}^{lm} \times (td_{ij}^{lm} - td_{ij}^{lm}) \quad (12)$$

d) Commercial kilometers:

The commercial kilometers represent distance crossed in kilometers that the transport company has to assure. This distance is generally the subject of a contract between the state and the transport companies. So, these companies are called to assure a predetermined number of kilometers of service a year. Every disturbance that affects the network traffic, can decrease/increase the crossed commercial distance and afterward to degrade the level of service. Hence, we will minimize the trade-off between a theoretical and real crossed kilometers for any vehicle in the network.

$$KM = \sum_{V_i^l \in V^H} \sum_{S_j^m \in S^H} a_{ij}^{lm} \times a_{ij}^{lm} \times d_i^l(S_j^m, S_j^m) \quad (13)$$

With $d_i^l(S_j^m, S_j^m)$ is the distance crossed by a vehicle V_i^l between these two stations.

e) Quality of service:

Different companies may have different measures of the quality of the service, but all of them coincide in the importance of this criterion. Some examples of measures of

the quality of the service are: the number of not served stations, the number of vehicles and drivers changes, and finally the number of transshipments (Not to confuse with correspondences). This criterion was formulated as follow:

$$SQ = \sum_{V_i^l \in V^H} (n_change(V_i^l) + n_trans(V_i^l) + n_stat(V_i^l)) \quad (14)$$

With $n_change(V_i^l)$, $n_trans(V_i^l)$, $n_stat(V_i^l)$ are respectively the numbers of vehicles and drivers changes, of transshipments and of no served stations.

2.4 Constraints

Several constraints should be taken into account during the real-time regulation of the traffic of a collective urban transport network. They can be related to the temporal configuration (vehicles) or spatial (stops) of the network. So, we consider the following constraints:

Each vehicle V_i^l passing by a given point has a unique origin point and goes to a unique immediate destination point:

$$\sum_{S_j^m \in S^H} x_{ijk}^{lmr} = a_{ij}^{lm} \quad (15)$$

The minimal time interval between V_i^l and V_j^l its first successor V_i^l at the stop S_j^m is stated as follow:

$$td_{i^l j}^{lm} - td_{ij}^{lm} \geq Inter_{\min}^l \quad (16)$$

The limit on the stop time of V_i^l at the station S_j^m is represented by the following constraint:

$$td_{ij}^{lm} - ta_{ij}^{lm} \geq ts_{ij}^{lm} \quad (17)$$

The time limits on the connection or transfer durations are presented by the following inequality:

$$Trans_{\min} \leq y_{ii^l}^{ll^m} \times (td_{i^l j}^{ll^m} - td_{ij}^{lm}) \leq Trans_{\max} \quad (18)$$

The vehicle load can not exceed the allowed maximum load:

$$C_{ij}^{lm} \leq C \max_{ij}^{lm} \quad (19)$$

Our regulation problem can be formulated as a multiobjective optimization problem; it can be stated as follow:

$$\begin{cases} \min \{ \Delta(WT), \Delta(TT), \Delta(RT), \Delta(KM), \Delta(QS) \} \\ \text{subject to: (15), (16), (17), (18) and (19)} \end{cases} \quad (20)$$

With $\Delta(x)$ is the variation of the criterion between the theoretical and the regulated states of the network.

We present in the following paragraph, a proposed decisions generation and evaluation module.

III A PROPOSED STRATEGIES EVALUATOR

As mentioned in the introduction, one of the most difficult and important tasks of the regulator during his/her mission of decision-making is the evaluation of the possible and feasible solutions (decisions) according to his/her preferences represented by the decision criteria previously formulated.

Hence, we present in this paragraph the developed decisions evaluator and the conceived decisions generator used to confirm our evaluation module (fig.2).

Indeed, from the regulators knowledge and experience and from their training brochures supplied by our industrial partner (SEMURVAL), we were able to realize an evaluation module of decisions strategies for a disturbed transport network regulation. Actually, this module is able to evaluate eleven classes among the twelve decisions classes used by the regulators at the SEMURVAL Company. Every class has its own sub evaluator that measures the application impact of a decision belonging to this class on the state of the disrupted network; this is realized by comparing the criteria values before and after the application of the decision to evaluate. However, this evaluator mono-entered can evaluate only a single decision at the same moment. So, we improved this module to make it able to evaluate five decisions all at once and classify them according to the regulator preferences.

Finally, to confirm our decisions evaluation, a decisions generator was realized. This generator has the role to construct automatically five feasible decisions according to the disturbance circumstances. Before calling the module of evaluation, our decisions generator must wait the validation of the regulator which can possibly modify, cancel one or some decisions. This generator is a rules base of type if (condition) then (action), based essentially on the conditions of application of every decisions class. If the disturbed vehicle, for example, is not far from a terminus station the first decision which will be generated is a regulation in terminus or an on-line half-turn. On the other hand, if the disrupted vehicle is far from a terminus, we generate at first an on-line regulation or an on-line express or an injection of an extra vehicle.

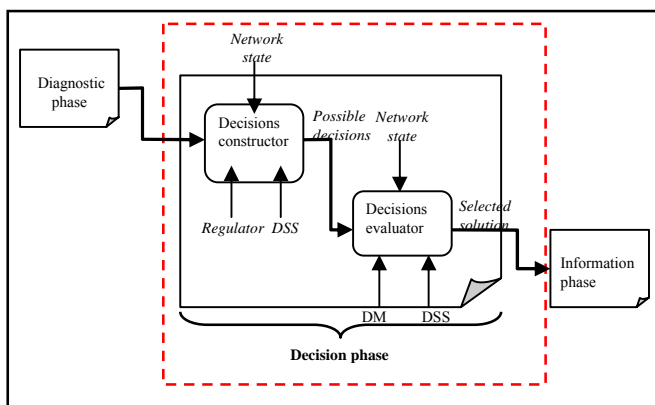


Fig.2. Decisions construction and evaluation

3.1 Decisions coding:

The coding of every decision class corresponds to data supplied to the evaluator by the decisions generator or by the regulator himself.

1- Deviation

This decision consists in the deviation of one or some vehicle(s) on a route or a part of route which follow(s) a faster route other than the regular one to compensate the delay and to assure service travellers in the next terminus or in any other station on the line. This decision was coded as follows:

Line	Vehicle(s))	Station begin	Station finish	Deviation (target)
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2-The on-line express

A disrupted Vehicle follows the route of the regular line assuring only the stops of descent for the on board customers. It was coded as follow:

Line	Vehicle	Station begin	Station finish	Arrival terminus
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3-The on-line half-turn (the go back)

It consists of the abolition of a part of journey to put back a vehicle on the theoretical timetable, to a return point, further to an important delay of this disrupted vehicle.

Line	Vehicle	Beginning station	Departure terminus
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4-The half-turn with drivers and vehicles exchanges

A disrupted is caught by the following one less charged on the time. The vehicle on the time tranships his customers on the late one and we exchange the two drivers. So, the late vehicle continues service on the on-time vehicle timetable. The on-time vehicle took the number of the late one, turns back and takes the theoretical timetable of the theoretical vehicle. It was coded as follow:

Line	Vehicle(s))	Beginning station	Departure terminus
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5-overtaking and service in descent only

A disrupted vehicle is caught up by the following one on the time. The second walks past the first and assures service normally. The exceeded vehicle continues journey but assures only the stops of descent. It was coded as follow:

Line	Vehicle	Station begin	Arrival terminus
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6-departure delayed in the terminus

In case where a disrupted vehicle having a delay superior to its beating time in the arrival terminus, we delay the previous car in the terminus by a half of the real delay value of the disrupted vehicle. It was coded as follow:

Line	Vehicle	Previous vehicle	Arrival terminus
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7-The drivers and vehicles exchanges

A disrupted vehicle is caught up by its following one, then transshipment of the travellers of the second vehicle towards the first more loaded, and exchange of drivers and the vehicles numbers. The second vehicle, which is empty, follows a deviation until it returns at the theoretical timetable of the first. The disrupted vehicle continues the service on the theoretical timetable of second one. It was coded as follow:

Line	Vehicle s 1 and 2	Station begin	Station finish	Deviation (target)
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8-The shortcut

A disrupted vehicle is to two minutes in front of its following one that is on time. The disrupted vehicle driver informs his clientele that he is not going to serve a part of the line and travellers wishing to come down on the not served part have to pass in the following car. The disrupted vehicle starts again by the shortcut resume its on-line theoretical timetable. It was coded as follow:

Line	Vehicle	Station begin	Station finish	Deviation
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9- Injection of a reserve and an available

It consists of the injection of a reserve (vehicle) and an available (driver) on the theoretical timetable of a disrupted vehicle; this decision can be used because of a delay or of a breakdown of a disrupted vehicle. It was coded as follow:

Line	Vehicle	Station begin	Station finish	Departure terminus
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10-regulation in terminus

It consists in making departures advanced or delayed on a terminus to restore on-line regularity by acting on one or two downstream and upstream vehicles, following the importance of the disrupted vehicle delay. It was coded as follow:

Line	Vehicles	delays	Arrival terminus
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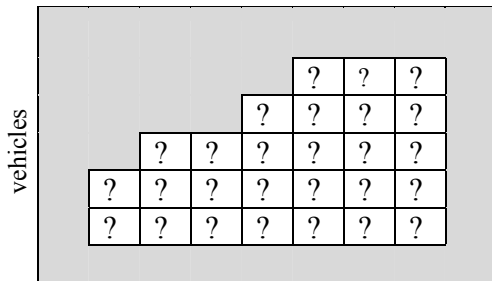
This decision can be considered as a particular case of the on-line regulation. Indeed, here one determines delays to impose on vehicles in their passage in the terminus (only a single station).

11 -on-line regulation

This decision consist of delaying two to three upstream and downstream vehicles of a disrupted vehicle to avoid excess load on this one, to help it to not increase the delay and to restore the intervals regularity.

This decision is used by the regulators for 90 % of the cases of disturbances, it is reliable and easy to implement. It was coded as above: the cells illustrate the delays to impose on the different vehicles at different stations belonging to the disturbance zone. However, the calculation of these delays in a way to obtain one solutions optimal or close to the optimal is very difficult. This problem was shown NP-hard Multi objective Optimization Problem (MOP) by the authors of [1]. Therefore this decision class deserves a particular treatment. For this decisions class, we propose a fuzzy evolutionary algorithm based on a genetic coding representing the decisions on a set of vehicles affected by the disturbance. The used coding is the same as that proposed in [1]. The proposed approach will be described in the following paragraph.

Stations



3. 2 A proposed approach for the on-line regulation

There are two major approaches for MOP. One approach is to transform the original problem into a single-objective problem using techniques such as the weighted-sum method. In this case, if the decision-maker (DM) is not satisfied with it, he/she must repeat the same procedure until a final solution is reached. The other approach is to find a group of Pareto-optimal solutions all at once. The DM can then choose a satisfying solution from among them considering tradeoffs between objectives, but it is difficult to select a final solution especially when the scale of problem is large [14][16][17].

In both these cases, the solution depends on the DM's preferences, and not only the search of solutions but also the decision making is important. Such preferences are generally of a subjective nature and could be well modelled using fuzzy logic [6] [7] [15].

In addition, during the recent past, multiobjective evolutionary algorithms are subject to an increasing attention among researchers and practitioners mainly because of the fact that can be suitably applied to find a set of Pareto-optimal solutions in one single simulation run [2][7][9]. However, the trade-off between obtaining this set as a well-converged and well-distributed as possible and obtaining that in a small computational time is an important issue in multi-objective evolutionary optimization [4].

To reach these objectives (Take into account DM's preferences and distribute obtained solutions as widely as possible with a small computational time), we developed our hybrid approach based on a fuzzy evaluation method and an evolutionary algorithm [5] [14] using the Pareto ε -dominance concept. Thus, we provide the regulators with evaluated and classified decisions. The proposed approach is based on the two following stages:

Fuzzy multi-objective evaluation

As we indicated previously, the solution of MOPs depends on the DM's preferences which are generally of a subjective nature. The use of fuzzy sets is useful for expressing such preferences. Furthermore, in conventional fuzzy set theory, "fuzziness" is provided in terms of membership function. On the other hand, Takatori [17] has proposed expressing "fuzziness" by an unsatisfying function, which has a one-to-one correspondence with the membership function, for optimization problems. Therefore, we used the unsatisfying functions to express the preferences of the decision-makers, in such a way; the proposed fuzzy multi-objective evaluation will be based on the following steps:

1) 1st step: determination of lower-bounds

To reduce the space of search and to characterize the limits of feasible solutions, we determined for every criterion a lower-bound such as:

$$\forall x \in \Omega \quad f_q(x) \geq f_q^* \quad (14)$$

where Ω is the space of feasible solutions.

The lower-bounds can be very useful to evaluate and judge the obtained solutions precisely. In our regulation case, the lower-bounds values correspond to those of three criteria in the normal state (traffic theoretical state). Moreover, it is coarse that in the case of an on-line regulation, the values of the criterion of the quality of service and the criterion of commercial Kilometres remain the same before and after regulation (this decision does not modify the route to be followed and does not entail changes of vehicles or drivers, or transhipments). Hence, we consider here only the other three criteria of regularity, transfer time and route time.

2) 2nd step: fuzzification

To be able to erase the influence of the difference between the units of measure of various objectives functions, and also to minimize effects due to the differences of beaches of variation of magnitude between objectives functions, we use a

simple application of the fuzzy logic based on the following stages:

- To each feasible solution x , we associate a vector. This vector will characterize by its components the 3 objectives to be optimized:

$$f(x) \in [AT^*, +\infty[\times [TT^*, +\infty[\times [RT^*, +\infty[$$

$$f(x) = (WT(x), TT(x), RT(x))^T \quad (22)$$

with WT^* , TT^* and RT^* the values of the lower-bounds computed in the first step.

- In particular, let H a chosen heuristic and f_q^H the best value of the q^{th} objective function given by the considered heuristic,

- For each vector $f(x)$, we propose a fuzzification of its components $f_q(x)$ according to their positions in the intervals $[f_q^*, f_q^H + \varepsilon_q]$ where ε_q is a little positive value designed to avoid the problem of dividing by zero (when $f_q = f_q^H$) and formulated as shown in (14).

$$\varepsilon_q = 0.01 \cdot f_q^* \text{ if } f_q = f_q^H; \text{ else } \varepsilon_q = 0 \quad (23)$$

The two considered fuzzy subsets are the following ones:

- G_q : The subset of the good solutions according to the q^{th} objective.
- B_q : The subset of the bad solutions according to the q^{th} objective.

The fuzzification is applied using the membership function as shown in Fig. 3.

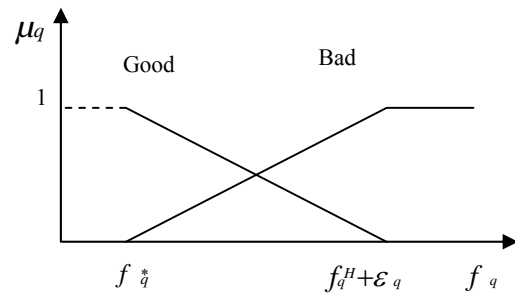


Fig.3 Fuzzy logic application for solving scale problem

Thus, to each vector $f(x)$, we associate two vectors $\tilde{f}_G(x)$ and $\tilde{f}_B(x)$ such that:

$$\tilde{f}_G(x) = (\mu^G(WT(x)), \mu^G(TT(x)), \mu^G(RT(x)))^T \quad \text{and}$$

$$\tilde{f}_B(x) = (\mu^B(WT(x)), \mu^B(TT(x)), \mu^B(RT(x)))^T \quad (24)$$

where:

$$\begin{aligned}
\mu^G(f_q(x)) &= \frac{f_q^H - f_q(x) + \varepsilon_q}{f_q^H - f_q^* + \varepsilon_q} & \text{If } f_q(x) \in [f_q^*, f_q^H + \varepsilon_q]; \\
\mu_q^G(f_q(x)) &= 0 & \text{if } f_q(x) \geq f_q^H + \varepsilon_q; \\
\mu_q^B(f_q(x)) &= 1 - \mu_q^G(f_q(x)) & \text{and}
\end{aligned} \tag{25}$$

Thereafter, the quality of each solution x is characterized by the vector $\tilde{f}_G(x)$ whose components are homogeneous and belong to the same interval $[0, 1]$.

3) 3rd step: Formulation of the fuzzy evaluation

After the fuzzification stage, we can transform our original problem into the following one:

$$\begin{aligned}
\max \{ \mu_1^G(WT), \mu_2^G(TT), \mu_3^G(RT) \} & \tag{26} \\
\text{Subject to the same constraints.} &
\end{aligned}$$

4) 4th step: Introduction of the unsatisfying functions

In the fuzzy set theory initiated by L. Zadeh, the degree of fuzziness is expressed by a membership function $\mu(x)$ in the interval $[0, 1]$, where x is the variable. The membership function $\mu(x)$ can be transformed into the following function $\tau(x)$ in the interval $[0, \infty]$

$$\tau(x) = \frac{1}{\mu(x)} - 1 \tag{27}$$

This function $\tau(x)$ is designated the unsatisfying function, it has a one-to-one correspondence with a membership function, so it is possible to express fuzzy set theory by using the unsatisfying function. Besides, it has been shown that using an unsatisfying function makes it easier for the DM to incorporate vague knowledge and information based on his/her experience, as opposed to using a membership function. For that reason, we now transform our fuzzy satisfying optimisation problem into the minimization of the unsatisfying rates:

$$\begin{cases} \min \{ \tau(WT), \tau(TT), \tau(RT) \} \\ \text{with } \tau(f_q) = \frac{1}{\mu_q^G(f_q)} - 1 \end{cases} \tag{28}$$

Multi-objective optimization

In this section, we are interested in the resolution of the on-line regulation problem itself. Indeed, we applied a Multi-Objective Evolutionary Algorithm (MOEA) using the ε -dominance concept and based on a genetic coding representing the decisions on a set of stops and vehicles affected by the disturbance (Delay to be imposed on vehicles to find the normal state after the appearance of a disturbance). The ε -MOEA used in this study is the improved variant of that proposed in [4]. We use two co-evolving populations: a parent population $P(t)$ and an archive population $E(t)$ (where t is the iteration counter).

The MOEA begins with an initial population $P(0)$ created earlier by a local search algorithm. The archive population $E(0)$ is assigned with the ε -non-dominated solutions of $P(0)$. Thereafter, two solutions p and e , one each from $P(t)$ and $E(t)$ are chosen for mating. To choose these two solutions, we use the same strategies used in [3]. After this selection phase, solutions p and e are mated to create one offspring solution. For its inclusion in the archive, the offspring is compared with each member in the archive for ε -dominance. To make this comparison, every solution in the archive is assigned an identification vector $B = (B_1, B_2, B_3)^T$ of three components representing the unsatisfying functions related to our three criteria as follows:

$$B_q(f) = \left\lfloor \frac{\tau(f_q)}{\varepsilon_q} \right\rfloor \tag{29}$$

where ε_q is the allowable tolerance in the q -th objective below which two values are insignificant to the user. This ε_q value is the same as the ε used in the ε -dominance definition.

Then the same method used in [4] is made. The above procedure is continued for a specified number of iterations and the final archive members are reported as the obtained solutions. The use of the ε -dominance criterion has two advantages: it helps to reduce the cardinality of Pareto-optimal region and it ensures that the solutions diversity is preserved.

4 Simulation results

In order to evaluate the efficiency of the suggested approach, we present here a scenario extracted from the urban transport network of Lille (real data). We consider the bus line 27 (noted B) and the tramway line Lille-Roubaix-Tourcoing noted T. The disturbance is detected at $t_{\text{dis}}=12:24$. It is caused by a technical problem at the tram line T, obliging the tram noted V_2^T to stand 7min at the stop S_2^T . This tram-line has a frequency of 1 tram per 10 minutes. The station S_2^T is situated at 10 min from a connection node that we note N, where a connection is planned at 12:40 with a bus V_1^B from line B, which has a frequency of one bus every 20 min. however, because of the disturbance, V_2^T would arrive at 12:43 at N, so the connection would not occur. The rate of correspondence from trams towards buses is of 10 % and that from the buses towards trams is 20 %. Let us suppose that the arrival rate is constant and equal to 2 passengers per minute.

1) Determination of the regulation horizon

The first stage of our regulation process consists of the determination of the spatiotemporal horizon of regulation. So, we use the method explained in the paragraph 2.1. We

calculate at first the rate $\frac{V_2}{V_1}$ of disrupted vehicle average speeds before and after the disturbance:

$$\frac{V_2}{V_1} = \frac{10}{10+7} = \frac{10}{17} \Rightarrow \tan(\alpha) = \frac{7}{17}$$

a) For the tram line: $f = 10$

$$N_{up}^T = E\left(\frac{r(1-\tan(\alpha))}{f \tan(\alpha)}\right) + 2 = E\left(7 \frac{(1-7/17)}{10 \times 7/17}\right) + 2 = 3$$

According to the equation 6:

$$N_{down}^T = 3 - 1 = 2$$

Therefore, the total number of the line L_{disr} is:

$$N_{up}^T = 3 + 2 + 1 = 6$$

Then the stations of the disrupted line to be included in the disturbance zone were determined using the timetable. There are 7 stations from this line to be considered.

b) For the bus line $f = 20$

$$N_{up}^B = E\left(\frac{r(1-\tan(\alpha))}{f \tan(\alpha)}\right) + 2 = E\left(7 \frac{(1-7/17)}{20 \times 7/17}\right) + 2 = 2$$

And also: $N_{down}^B = N_{up}^B - 1 = 1$ so the total bus number is:

$N_T^B = 2 + 1 + 1 = 4$, then we use the same method to determine the bus stations number. There are 7 stations.

The second step of our regulation process consists of the decisions construction.

2) Decisions construction

As the disrupted line is a line streetcar, the generator of decisions by using its base of rules, proceeds to eliminate (to filter) not practicable decisions. So, it eliminates the following decisions:

- Deviation: This action of regulation concern buses only, because it requires a special architecture of the network: it can be realized only if we have the possibility of deviating a regular route.
- The departure delayed in terminus: this decision can not be undertaking in our case because of that a disrupted vehicle far from the arrival terminus.
- The regulation in terminus
- The overtaking : it can not realized: a same motive as for the deviation
- Vehicles and drivers exchanges: this decision requires a route deviation, and this is impossible.
- The injection of an extra vehicle: This decision must not be taken except in case of a big disturbance and lastly appeal, because it costs expensive to the network developer.
- The on-line half-turn: This decision requires a return loop on the line, it is misadvised for the streetcar lines, and it asks an important effort on behalf of the regulator.
- The on-line half-turn with drivers and vehicles exchanges: it not realisable for the same motif as for the on-line half-turn.

In continuation, our decisions generation module, by using information relative to the early defined disturbance zone (horizon of regulation) builds the following decisions corresponding to the practicable decisions classes:

- The on-line regulation: To build a decision of this kind, we use a proposed approach to the paragraph 3.2. Once the regulation horizon created, we use the collected data to build the solutions coding and execute our fuzzy-evolutionary approach explained in (§ 3.2). The chromosomes of our problem are coded as follows: for the tram-line, we use an array with 6 lines corresponding to the vehicles included in the disturbance zone and 7 colons for the stations. Also, for the bus line we use an array with 4 lines and 7 colons. The chromosome cells illustrate the decisions (delays to be imposed) to undertake for the vehicles of V^H at different stops of S^H . Our approach will try to find the best combination of delays to be applied to two lines concerned by the disturbance. It fills so the corresponding array to every line and gives us in exit the best obtained decision. For the ε -MOEA, we have

T	S_0^T	S_1^T	S_2^T	S_3^T	N	S_5^T	S_6^T
V_0^T	0	0	0	0	0	0	0
V_1^T	0	0	0	0	1	2	1
V_2^T	0	0	0	0	0	0	0
V_3^T	0	1	0	0	0	2	1
V_4^T	0	1	1	0	0	1	1
V_5^T	1	0	1	1	0	1	0

operates on the lines of chromosome; it acts only on the decision variable ε_{ij}^{lm} in the chromosome cells. Two breakpoints are chosen randomly and the exchange of the genes between the individuals is made only between the same vehicles. The crossover probability is set at 0.8. The mutation operates by random changes on the stops variables. The mutation probability is set at 0.05. For 5000 generations and a population of 100 individuals, the obtained results are given in the table 2; the time of execution is included between less of 15 seconds. For our example, here is obtained decision:

	$\Delta(WT)$	$\Delta(TT)$	$\Delta(RT)$	$\Delta(KM)$	$\Delta(QS)$
On-line regulation	6%	0%	6.5%	0%	0
On-line express	13.1%	0.35%	1.5%	0%	3
shortcut	15%	0.35%	0.9%	0%	4

Table.1. Delays to be imposed on the tram-line vehicles

Table.2. Delays to be imposed on the bus-line vehicles

- The on line express: This decision concerns only the disrupted vehicle for which we try to stabilize its delay. It was tested on the entire zone included between the disrupted station and the station S_{down} . To build a decision of this kind, our decision generator, uses for its coding that the station begin is the disrupted one and the final station is S_{down} .
- The shortcut: As the previous action, this decision concerns only the disrupted vehicle which does not have to stop between the disrupted station and the station in which returns in its theoretical timetable. To build a decision of this class, the generator determines at first the final station corresponding to the return to the theoretical timetable and then it considers the disrupted station as a begin one.

3) Decisions evaluation

The last stage of the regulation process consists to the decisions evaluation according to the criteria. To make that, our decisions evaluator calculates the disrupted planned departure and arrival times for every vehicle at every station. Thus, we can estimate the impact of the disturbance on the network traffic. Then, the new timetables, represented by the arrival and departure at the stops must be computed. The loads of the different vehicles should also be estimated. After these preliminary calculations the evaluator determines the percentage of improvement or degradation of every criterion by comparing its disrupted and regulated value.

We present in the follows the evaluations of three practicable decisions, namely on-line regulation, on-line express between

the station S_2^T and the station S_6^T , and the shortcut among these two stations.

If the regulator is satisfied with this classification, he has to apply on-line regulation decision. We notice a return to the normal state for the correspondence criterion and the reduction of the total waiting time of the customers. This is very logical because the regulator prefers that threatened correspondence will be occurring and he does not give the same importance for the other criteria. However, taken decision does not improve enormously the total route time.

This example shows the efficiency of our evaluation and optimization approach and the quality of the obtained solutions.

5 Conclusion and perspectives

In this paper, we presented a main part of a decision support system for the urban transport networks regulation and evaluation. First, we proposed a new mathematical formulation of the transport regulation problem. Indeed, we explained an efficient method for the regulation horizon determination and we introduced two new criteria for the decisions evaluation. A proposed evaluation module uses a hybrid approach based on evolutionary algorithms and fuzzy logic and uses ε -dominance concept. We have confirmed this method by using real data of a disrupted transport network and obtained results are satisfactory.

We have compared the results of our approach for the on-line regulation and those of the approach proposed in [1] and noticed a considerable improvement of the quality of solutions, this is due to the use fuzzy logic evaluation, and to the representative capacity of fuzzy sets used in this approach.

On the other hand, the use of the ε -dominance criterion have two advantages:

it helps to reduce the cardinality of Pareto-optimal region and it ensures that the solutions diversity is preserved.

There are many goals of our future research. First, we will validate a proposed decisions builder and evaluator by using more lines and more disturbances. We shall also want to develop a classifier of decisions using the Choquet integral [7] to facilitate the task of the best decision choice and to take into account the interaction between the regulation's criteria which are not independent. At the end, we test the product developed on the transport network of the SEMURVAL Company.

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