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Multi-criterion Tabu Search to Solve the Dynamic Carpooling Based on the Choquet Integral Aggregation

Sondes Ben Cheikh and Slim Hammadi
École Centrale de Lille, LAGIS FRE CNRS 3303, BP 48, 59651 Villeneuve d'Ascq Cedex-France
Email: {sondes.ben-cheikh, slim.hammadi}@ec-lille.fr

***Abstract*—Carpooling consists in sharing one's personal vehicles with one or several passengers in order to share the related costs but also reduce traffic and CO_2 emissions. Today, there are several studies that revolve around dynamic carpooling. The problem is how to assign every new passenger's request to one or more vehicles. This assignment must be done in real time. However, most of these studies still remain in embryonic stage regarding automation and real time aspects. In addition, there is another big handicap, due to the problem's high complexity, concerning the way to make the process perform efficiently. Therefore, this study adopts a Multi-criterion Tabu search (MTS), which is an evolutionary method based on explicit memory systems and several searching strategies designed to avoid the entrapments by local solutions. Then, to obtain a rigorous and meaningful evaluation of our solution, we use an original aggregative approach based on Choquet Integral which take into account the interaction, the compensation and avoid redundancy between criteria. Finally, to assess the merits of our approach we present a simulation study based on travel demand data from metropolitan of Lille-France. The simulation results indicate that the use of metaheuristic optimization methods improve the performance of our dynamic carpooling system.**

***Index Terms*—dynamic carpooling, tabu search, choquet integral**

I. INTRODUCTION

The increase in commuting time, traffic congestion and rising fuel prices, lead to a questioning of the massive use of the private car. Moreover, taking into account environmental awareness and sustainable development policies pave the way for innovative eco-mobility practices. Hence the emergence of car sharing is one of the planned rationalization of the use of the private car solutions. In this context, carpooling is a concept that brings a great interest. It is defined as the common use of a vehicle by an unprofessional driver and one (or more) passenger (s) to carry out all or part of a common path.

Following criteria reservation management adopted within the system, the work done so far can be divided into two categories. The first category is based on a static reservation management while the second deals with the dynamic real-time aspect. In this context, we present a non-exhaustive list of what could be done around this by making a distinction between:

- Operating systems, such as carpooling sites that remain for the most open and non-optimized systems.
- The academic studies done for modeling and optimization of such systems.

Projects official carpooling have been around since the mid-1970 and are released as online sites through which members can post carpool requests and retrieve relevant offers (e.g. Covoiturage.fr, carpooling.com). The principle is simple: members must introduce their personal coordinates (origin, destination, time ...). Then, they can directly contact each other to agree on trips' details. However, static systems require booking in advance based on a static reasoning, regardless of instantaneous events. To address this deficit, dynamic carpooling systems are developed with a real time service management (e.g. greenmonkeys.com, covivo.fr). The mobile computing with current advances in geographic location systems, mobile communications (e.g. GPRS, Wimax), new mobile devices (e.g. PDA, mobile phone) and navigations platforms overcame this limitation. This type of carpooling has great development potential because of the flexibility of the service, it aims to provide through its principles: real-time route optimization and guaranteeing a reliable service.

On the academic side, several tools and approaches have been proposed to solve the problem of carpooling in its dynamic context. However, most carpooling studies have focused on the to-work problem (from different origins to a common destination) or the return-from-work problem (from the same origin to different destinations). In this context, R. Baldacci [1] examined carpooling as a transportation service organized by a large company which encouraged its employees to pick up colleagues while driving to/from work, to minimize the number of private cars traveling to/from the company site [2]. On the other side, suitable model developed for solving practical many-to-many carpooling problem. To solve this problem, several studies have adapted the Djikstra algorithm to find the shortest path [3], [4]. Moreover, trying to take advantage from new technologies, mobile

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and lightweight devices, systems integrating the multi-agent concept have emerged [5], [6].

Nevertheless, those systems are either operating or not and even if some of them succeeded, they still need improvement. As optimization and dynamicity are the most lacking aspects, we are interested in setting up an optimized dynamic carpooling system which manages a set of offers and requests and proposes optimized assignment passenger/vehicle which minimize travel time, its cost and the CO_2 emission quota.

II. DECISION VARIABLES

We note R_p (t) = { $R_l, R_2, \ldots R_l, \ldots, R_{n_r}$ } the set of n_r instantly received demands for $P = \bigcup_{l=1}^{n} \{P^l\}$ which is the set of *n* passengers ($n_r \leq n$). Equation (1) shows passenger P^l request's formulation:

$$R_l(t) = \left(P^{l-}, P^{l+}, d^l, a^l, Q^l\right) \qquad (1)$$

where moving preferences are specified:

- P^{l-}, P^{l+} are respectively the origin and the destination node asked by the passenger P^l.
- d^l, a^l indicate the earliest departure time and the latest Arrival time preferred by P^l.
- $Q^l \geq 1$ is the number of passengers including P^l who desire travel together.

Similarly, we note $O_V(t) = \left\{O_{V^1}, O_{V^2}, \ldots, O_{V^k}, \ldots, O_{V^m}\right\}$ the set of *m* vehicles offers received at time *t*, where $V = \bigcup_{k=1}^{m} \{V^k\}$ is the set of *m* vehicles expressing travel deals. Equation (2) shows the formulation of vehicle V^k 's offer:

$$O_{V^k}(t) = (V^{k-}, V^{k+}, MD^k, MA^k, L^k, C^k, h^k) \quad (2)$$

- V^{k-}, V^{k+} refer respectively the origin and the destination of the vehicle V^k with a capacity L^k. MD^k, MA^k indicate respectively the vector of the estimated departure time denoted D_i^k, and the vector of the estimated arrival time denoted A_i^k of the vehicle V^k on all nodes *i* between V^{k-} and V^{k+}. According to the traffic condition, these nodes correspond on the Intermediate Destinations specified by the driver in real time. Moreover, each vehicle V^k is characterized by a kilometric cost criterion that we note C^k and a criterion of emission rate of CO_2 per kilometer denoted h^k.

III. DEVELOPED APPROACH

To solve the multi-criterion dynamic carpooling, we propose a meta-heuristic approach called Tabu Search Algorithm (TSA) formally introduced by Fred Glover in 1989 [7]. This algorithm has a flexible memory to keep the information about the history search and employs it to create and explore the new solution in the search space.

A. The Assignment Process

In this study, we propose a Multi-criterion TSA (MTSA) for the Dynamic Carpooling Problem (DCP). Starting from an initial solution s_0, the algorithm moves at iteration t from s_t to the best solution in a neighbourhood $N(s_t)$ of s_t. To avoid cycling, solutions possessing some attributes of recently visited solutions are declared forbidden, or tabu, for a number of iterations, unless they constitute a new incumbent.

1) Data modelling

According to the estimated departure time and the distance between different origins of vehicles and passengers, the system starts by constructing the matrix of possible assignments Vehicle / Passenger in origins (DVM: Departure Vehicle Matrix) (Table I) .

TABLE I. MATRIX OF POSSIBLE ASSIGNMENTS VEHICLE / PASSENGER

P^l/V^k	V^1	V^2	$\ldots V^k \ldots$	V^{m-1}	V^m
P^1	*	X	X	*	*
P^2	X	*	*	X	*
… P^l …	…				
P^{n-1}	X	*	X	*	X
P^n	*	X	*	X	X

*: possible assignment X: Impossible assignment

Indeed, a passenger P^l can be assigned to a vehicle V^k only if the distance between his origin P^{l-} and the current position of the vehicle is less than the radius *R* which is the maximal path feasibly be made on foot (Figure 1). Likewise, a matrix TVM (Transit Vehicle Matrix) is generated representing all possible assignments Vehicle/Passenger in different transit nodes. In fact, a passenger P^l can be assigned to a vehicle $V^{k'}$ in the transit node only if it can deposit him at a maximum walking distance *R* from his final destination P^{l+} (Fig. 1).

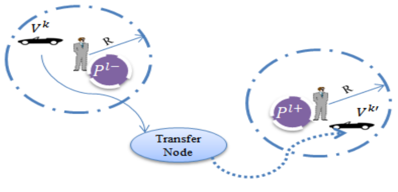


Figure 1. The possible assignment of P^l to V^k and $V^{k'}$

Among our data modeling, we have also a matrix INV (Interconnected Nodes between Vehicles) which presents all intermediate destinations of vehicles. We note $N = \bigcup_{i=1}^{nd} \left\{ N^i \right\}$, the set of nodes belong to the carpooling network (Table II).

TABLE II. MATRIX OF INTERCONNECTED NODES BETWEEN VEHICLES (INV)

N^i / V^k	V^1	V^2	$\ldots V^k \ldots$	V^{m-1}	V^m
N^1	*1*	*1*	*X*	*X*	*X*
N^2	*X*	*X*	*1*	*X*	*1*
… N^i …	…				
N^{nd-1}	*X*	*1*	*X*	*1*	*X*
N^{nd}	*1*	*X*	*1*	*1*	*X*

1: **If** N^i belongs to the itinerary of V^k, **Else**, X: Is not

2) *Construction of initial solution*

According to information from the matrix of possible assignments and the vehicles capacities, an initial solution is obtained by randomly assigning passengers to vehicles. Subsequently, the algorithm shall verify whether the passenger is assigned to the same vehicle in the departure and in the transit node. Otherwise, the passenger needs two vehicles to ensure his journey. Then the system checks if the two vehicles have a common intermediate destination.

3) *Tabu list*

Thanks to Tabu Moves, we can keep the search bias toward point with lower objective function values and escape from local optimum solution. In our case and in order to avoid returning to the local optimum already visited, the Tabu Move is define as the impossible transfer between vehicles V^k and $V^{k'}$ for the passenger P^l Then, the triplet { $P^l, V^k, V^{k'}$ } is declared forbidden and it is saved in the Tabu List.

4) *Neighbourhood construction*

To obtain the neighborhood solution, our system searches in the Tabu List the unallocated passengers and reassigns them to other vehicles. In case where the Tabu List is empty, the system chooses randomly certain passengers and reallocates them to other vehicles in order to avoid a local optimum solution.

5) *Aspiration criterion*

Since, the Tabu List may forbid certain worthy or interesting assignments vehicle/passenger possibly leading to a better solution than the best one found so far. An aspiration criterion is used to allow tabu assignments to be released if they are judged to be worth or interesting. In our case, the aspiration criterion is defined by the possibility that a vehicle can make a detour to retrieve a passenger in order to provide more flexibility. In other word, the aspiration criterion is to allow "excellent" Tabu Moves to be selected if the aspiration level is reached.

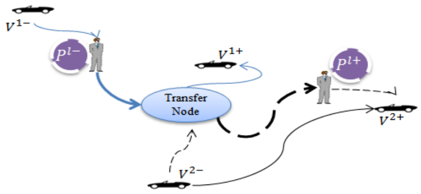


Figure 2. Example of Detour: V^2 made a detour to retrieve P^l

6) *The evaluation process*

a) *Evaluation criteria*

In this paper, we deal with five criteria to evaluate the quality of the current solution; the considered criteria to optimize are: the waiting time of the customers in origins and transfer nodes, the anticipated delay time and the journey time. Moreover, to improve the comfort of the customers, our system takes into consideration the economic and the environmental aspect. For this, the quality of the solution depends on the trip cost and the gain of CO_2 realized by each passenger.

- *The total waiting time*

This criterion aims to minimize the customers' waiting time in the departure point and in the transfer node. Therefore, for each passenger P^l assigned first to V^k then to $V^{k'}$, the waiting time in origin (i= P^{l-})is the difference between the departure time desired by P^l and the departure time of V^k Then, the waiting time in the transfer node corresponds to the difference between the departure time of $V^{k'}$ and the arriv (1)al time of V^k in the transfer node j. Subsequently, the P^l waiting time is formulated as:

$$WT_{lkk'} = Max(0,(D_i^k - d^l)*X_{lk} + (D_j^{k'} - A_j^k)*X_{lk'}) \quad (1)$$

where X_{lk} is a decision variable which is equal to 1 if P^l is affected to V^k, 0 otherwise.

Then, The total passengers waiting time at the different nodes is equal to:

$$TWT = \sum_{k=1}^{m} \sum_{\substack{k'=1 \\ k' \neq k}}^{m} \sum_{l=1}^{n} WT_{lkk'} \quad (2)$$

- *The total delay time*

This criterion seeks to minimize the delay time which corresponds to the difference between the desired arrival time specified by the passenger and the actual arrival time to its final destination (i= P^{l+}). It can be defined as follows:

$$WT_{lkk'} = Max(0,(A_i^k - a^l)) \quad (3)$$

Consequently, the total delay time is calculated as:

$$TDT = \sum_{k=1}^{m}\sum_{l=1}^{n} DT_{lk} * X_{lk} \quad (4)$$

- The total route time

The route time criterion consists of minimizing the total journey times aboard the various vehicles. For each passenger P^l assigned to V^k from *i* to *j*, the route time is stated as follows:

$$RT_{lk} = (A_j^k - D_i^k) * X_{lk} \quad (5)$$

We suppose that P^l was assigned to V^k at the departure point and to $V^{k'}$ at the transit point. Then the global route time is formulated as:

$$RT_{lkk'} = RT_{lk} + RT_{lk'} \quad (6)$$

Subsequently, to evaluate the solution, we need the total route time of all passengers which is determined as:

$$TRT = \sum_{k=1}^{m}\sum_{\substack{k'=1 \\ k'\neq k}}^{m}\sum_{l=1}^{n} RT_{lkk'} \quad (7)$$

- *Environmental criteria*

This criterion determines the improvement in terms of CO_2 established in both of the following cases:

-Passenger uses his own vehicle,
-Passenger chooses to carpool.

- CO_2 *emission quota without carpooling:*

$$IC_{lk_l} = h^{k_l} * distnace(P^{l+}, P^{l-}) \quad (8)$$

where IC_{lk_l} is the emission quota of CO_2 if the passenger P^l uses his own vehicle denoted V^{k_l} which is characterized by h^{k_l} , its emission rate of CO_2 per kilometer.

- CO_2 *emission quota with carpooling:*

$$SC_{lk} = \frac{h^k * RT_{lk} * AverageSpeed}{number\_of\_passengers\_in\_V^k} \quad (9)$$

where SC_{lk} is the emission quota of CO_2 for each passenger sharing the same vehicle V^k which is characterized by h^k . Hence, the gain of CO_2 per passenger is calculated as follows:

Without transfer:

$$Gain_{lk} = IC_{lk_l} - (SC_{lk} * X_{lk}) \quad (10)$$

With transfer:

$$SC_{lkk'} = SC_{lk} * X_{lk} + SC_{lk'} * X_{lk'} \quad (11)$$

So,

$$Gain_{lkk'} = IC_{lk_l} - SC_{lkk'} \quad (12)$$

In that case, the total environmental gain realized by all passengers is determined by:

$$TEG = \sum_{k=1}^{m}\sum_{\substack{k'=1 \\ k'\neq k}}^{m}\sum_{l=1}^{n} Gain_{lkk'} \quad (13)$$

- *The economic criterion*

According to the cost per kilometer C^k of each vehicle V^k , this criterion seeks to minimize the trip cost which is formulated as follows:

Without transfer:

$$CK_{lk} = C^k * RT_{lk} * AverageSpeed \quad (14)$$

With transfer:

$$CK_{lkk'} = CK_{lk} * X_{lk} + CK_{lk'} * X_{lk'} \quad (15)$$

Then, the total cost for all passengers is calculated by:

$$TC = \sum_{k=1}^{m}\sum_{\substack{k'=1 \\ k'\neq k}}^{m}\sum_{l=1}^{n} CK_{lkk'} \quad (16)$$

Thereafter, the aggregation criteria process is determined by applying the Choquet Integral taking into account the weighting, the interaction and the compensation between different criteria.

b) The choquet integral

The classical weighted arithmetic mean method is the most commonly used operator to aggregate criteria in decision making problems without further considering the interactions among criteria. On the contrary, the discrete Choquet integral proposed by Murofushi and Sugeno [8] has proven to be an adequate aggregation operator that extends the weighted arithmetic mean method by taking into *consideration the interactions among criteria.* It is possible to express the Choquet integral in case of 2 additive measures by using only the interaction index, as follows. Let $a_1, \dots, a_n$ be scores on criteria.

$$C_\mu(a) = \sum_{I_{ij} \succ 0} (a_i \wedge a_j) I_{ij} + \sum_{I_{ij} \prec 0} (a_i \vee a_j) |I_{ij}| + \sum_{i=1}^{n} a_i (I_i - \frac{1}{2} \sum_{j \neq i} |I_{ij}|) \quad (17)$$

where $\wedge$ et $\vee$ represent respectively the minimum and maximum.

To calculate the partial scores, we apply the fuzzification method used by our team [9] in order to make criteria homogeneous and evaluated in the same scale.

- *Interaction index and shapley values determination*

To be able to calculate the global score of each solution, we have to determine the Shapley values and interaction index between criteria (coefficients of Choquet integral). For reasons of simplicity, we suppose that the system manager can express, quantitatively or qualitatively, his preferences and it can give the interactions index.

$$\left[\begin{array}{cccccc} / & TWT & TDT & TRT & TEG & TC \\ TWT & 0.1 & 0.15 & 0.2 & 0 & 0 \\ TDT & 0.15 & 0.5 & -0.2 & 0 & 0.1 \\ TRT & 0.2 & -0.2 & 0,1 & 0.1 & -0.1 \\ TEG & 0 & 0 & 0.1 & 0.1 & 0.05 \\ TC & 0 & 0.1 & -0.1 & 0.05 & 0.2 \end{array}\right] = I_{ij} \qquad (18)$$

We note that values on the diagonal of this matrix represent the criteria importance, whereas the others represent the interaction index between criteria.

IV. MTSA TO SOLVE THE DCP

The Tabu Search begins by marching to a local minimum. Then, MTSA uses a neighborhood search procedure to iteratively move from one potential solution to an improved solution, until some stopping criterion has been satisfied. The procedure of MTSA can be described as follows:

MTSA for the DCP

Input: $P=\bigcup_{l=1}^{n}\{P^l\}$: *the set of n passengers*, $V=\bigcup_{k=1}^{m}\{V^k\}$: *the set of m vehicles*, INV, DVM, TVM, CT: Capacity Table, *MIS: Matrix of Initial Solution, MCS: Matrix Current Solution, TDD: Tolerated Detour Distance.*

Output: *MBS: Matrix Best Solution,* DVM, TVM, CT, Tabu_List, *Choquet Integral Score.*

```
Initialization
1.  For all passengers $P^l$ $\in$€ P Do
2.  For all vehicles $V^k$ $\in$ V Do
        3.  MIS [ $P^l, V^k$ ] =0
        4.  MCS [ $P^l, V^k$ ] =0
5.  MBS [ $P^l, V^k$ ] =0
6.  End for
7.  End for
8.  Tabu_List=$\phi$
9.  Initialize_Aspiration_Criterion(TDD)
10. Solution_Construction_Algorithm(INV,DVM, TVM, CT, MIS, Tabu_List)
11. Choquet_Integral_Evaluation(MIS)   //Multi-criterion evaluation {TWT, TDT, TRT, TEG, TC}
12. MBS←MIS
13. MCS←MIS
14. Define Terminated Conditions
Treatment
  1.  Done = False
  2.  Repeat
  3.  Select=random(3)// Select the Neighborhood research Space
  4.  Neighberhood_Algorithm(MCS, DVM, TVM, CT, Select)
  5.  Solution_Construction_Algorithm (INV, DVM, TVM, CT, MCS, Tabu_List)
  6.  If (Choquet_Integral_Evaluation (MBS)< Choquet_Integral_Evaluation (MCS)) Then
        7.  MBS←MCS
        8.  Update Choquet_Integral_Score
        9.  Update Tabu_List
  10. End If
  11. If MBS doesn't changed at a maximum number of iteration Then
        12. Aspiration_Algorithm( MCS, CT, Tabu_List) Go to 6
  13. End If
  14. If Terminated condition is satisfied Then
  15. Done = True
16. Until done= True
```

V. SIMULATION RESULTS

In order to improve the effectiveness of our approach and to study the merits of optimization for dynamic carpooling, we propose a ridesharing service in the French city of Lille (Nord department) during a transport's disturbance. Let's suppose that between 7 a.m. and 10 a.m a technical problem takes place on a section of the metro line 1 (yellow) and the bus 42 (green) (Fig. 3). We note that there are two poles of transfer between the two lines in both directions.

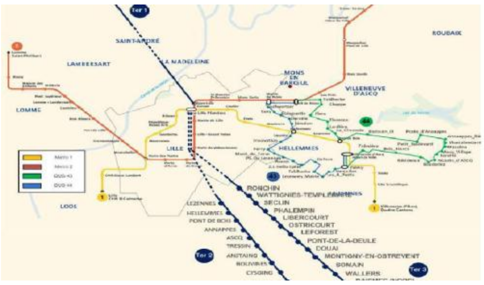
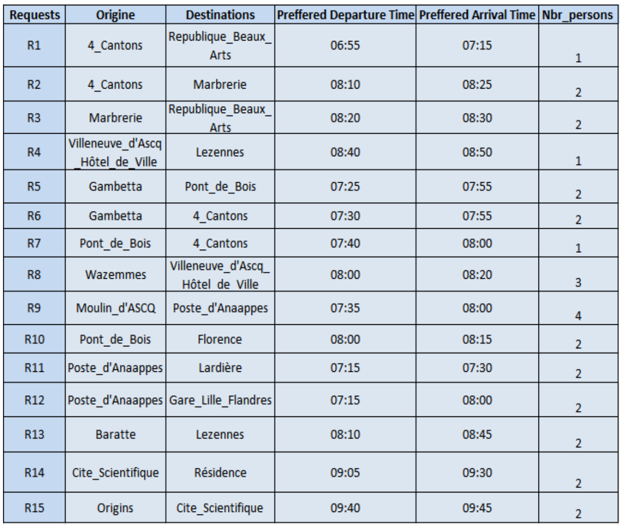


Figure 3. The transportation network of Lille

Therefore, we present here a scenario composed of 30 passengers subdivided into 15 requests, and 20 vehicles travelling on the network. Each passenger or group of passengers must express their preferred departure and arrival times (Table II).

TABLE III. REQUESTS DATA



Requests	Origine	Destinations	Preffered Departure Time	Preffered Arrival Time	Nbr_persons
R1	4_Cantons	Republique_Beaux_Arts	06:55	07:15	1
R2	4_Cantons	Marbrerie	08:10	08:25	2
R3	Marbrerie	Republique_Beaux_Arts	08:20	08:30	2
R4	Villeneuve_d'Ascq_Hôtel_de_Ville	Lezennes	08:40	08:50	1
R5	Gambetta	Pont_de_Bois	07:25	07:55	2
R6	Gambetta	4_Cantons	07:30	07:55	2
R7	Pont_de_Bois	4_Cantons	07:40	08:00	1
R8	Wazemmes	Villeneuve_d'Ascq_Hôtel_de_Ville	08:00	08:20	3
R9	Moulin_d'ASCQ	Poste_d'Anaappes	07:35	08:00	4
R10	Pont_de_Bois	Florence	08:00	08:15	2
R11	Poste_d'Anaappes	Lardière	07:15	07:30	2
R12	Poste_d'Anaappes	Gare_Lille_Flandres	07:15	08:00	2
R13	Baratte	Lezennes	08:10	08:45	2
R14	Cite_Scientifique	Résidence	09:05	09:30	2
R15	Origins	Cite_Scientifique	09:40	09:45	2

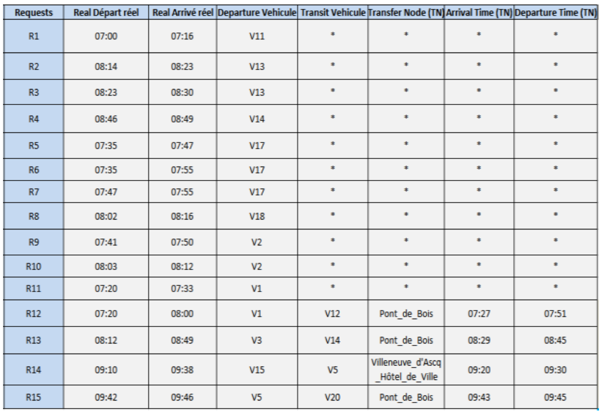
Our MTSA approach begins by generating the matrix of possible assignments vehicle/passenger. After the construction of the feasible solution comes the stage of evaluation which serves for attributing a global score calculated according to the importance of every criterion and the interaction between criteria. Then scores obtained by the best solution are shown in the following table:

TABLE IV. SOLUTION EVALUATION

TWT	TDT	TRT	TEG	TC	Global Score
0,8	0,9	0,6	0,5	0,7	0,98

Therefore, the best solution which corresponds to the highest score of Choquet Integral is stated as follows:

TABLE V. THE BEST SOLUTION GENERATED BY THE MTSA



Requests	Real Départ réel	Real Arrivé réel	Departure Vehicule	Transit Vehicule	Transfer Node (TN)	Arrival Time (TN)	Departure Time (TN)
R1	07:00	07:16	V11	*	*	*	*
R2	08:14	08:23	V13	*	*	*	*
R3	08:23	08:30	V13	*	*	*	*
R4	08:46	08:49	V14	*	*	*	*
R5	07:35	07:47	V17	*	*	*	*
R6	07:35	07:55	V17	*	*	*	*
R7	07:47	07:55	V17	*	*	*	*
R8	08:02	08:16	V18	*	*	*	*
R9	07:41	07:50	V2	*	*	*	*
R10	08:03	08:12	V2	*	*	*	*
R11	07:20	07:33	V1	*	*	*	*
R12	07:20	08:00	V1	V12	Pont_de_Bois	07:27	07:51
R13	08:12	08:49	V3	V14	Pont_de_Bois	08:29	08:45
R14	09:10	09:38	V15	V5	Villeneuve_d'Ascq_Hôtel_de_Ville	09:20	09:30
R15	09:42	09:46	V5	V20	Pont_de_Bois	09:43	09:45

To evaluate the efficiency of the best solution, we present the graphs below which summarize results for the 15 requests.

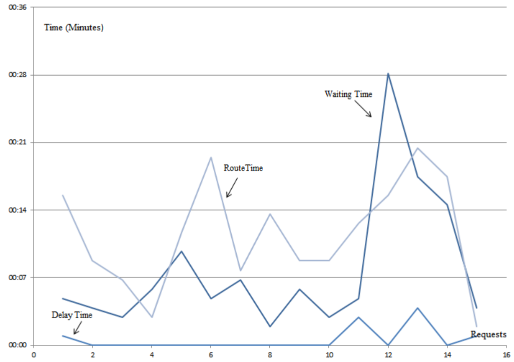


Figure 4. Values of WT, DT, and RT (minutes) / request

The Fig. 4 indicates that majority of passengers arrived at their destinations with an average waiting time of nine minutes, an average route time which may not exceed ten minutes and sometimes without delay.

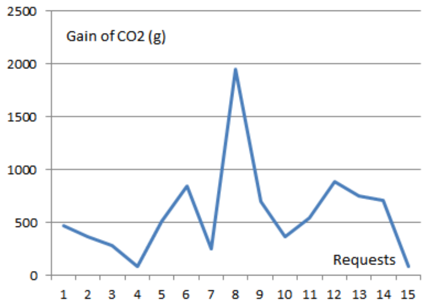


Figure 5. Gain Co_2(g) /request

According to Fig. 5 and Fig. 6, we note that the gain realized by each passenger may exceed 1500 g of CO_2 and the cost of travel may be less than one euro unlike the unified price of public transport tickets which does not take into account the traveled distance. Moreover, to measure the quality of our solution, we determine the performance rate for each time interval. This rate is obtained by dividing the total number of vehicles operating in this time interval by the number of served passengers including the drivers aboard these vehicles. More this rate converges to zero better the solution is efficient (Fig. 7).

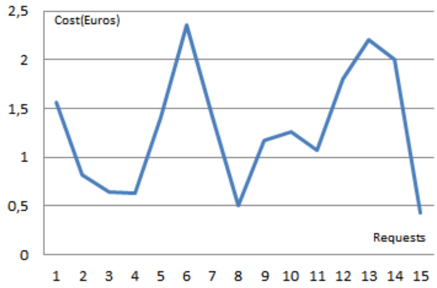


Figure 6. Cost (Euros) /request

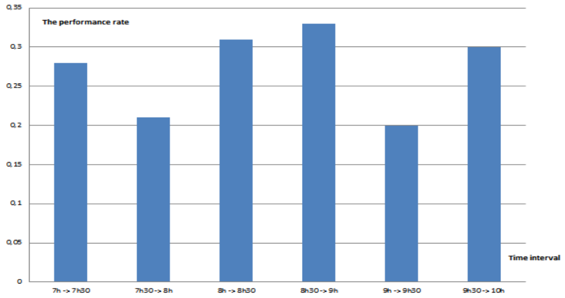


Figure 7. The performance rate

VI. CONCLUSION AND PERSPECTIVES

Our purpose in this paper is to develop a system which offers a real-time carpool solution and optimizes several criteria travel time, travel cost and environmental gain. Therefore, we propose the application of TSA as meta-heuristic method for DCP. However, this problem's high complexity constitutes a big handicap through the way to perform efficient process. Consequently, the DCP can be decomposed into multiple less complex tasks. Indeed, we will propose in future studies the network's subdivision principle in conjunction with the Multi-Agent concept to highlight the decentralized parallel process…

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