Intelligent Methods and Models in Transportation

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Abstract. This work analyzes many different models and algorithms in the literature for the optimization of routes and frequencies of buses, necessary in the framework of the support tools development to take decisions for the collective urban public transportation systems design. The problem is NP-hard, for which diverse heuristic procedures to resolve it have been proposed in the literature. The methods that pretend to be more applicable are those that permit interactivity.

The main purpose of this work is to propose an efficient method for optimizing bus routes and their frequences considering heterogeneous vehicles, so that the final user obtains a feasible solution in a reasonable computation time. The optimization method proposed in this paper take into account a multi-objective function under diverse restrictions and an optimizer at two levels using two metaheuristic algorithms. This work presents a model based on two Genetic Algorithms.

Keywords: Collective Urban Transport, Routes Generator, Combinatorial Complexity, Evolutionary Algorithms, Genetic Algorithms, Multi-objective

1 Introduction

Planning for an urban transport system involves determining a collective plan of routes, frequencies, schedules, assignment of coaches and staff, as best as possible.

The system, based on input data and a large number of restrictions previously established, must determine, in an effective way, an optimal design of routes, which provide a fixed level of service and cover the demands required respecting the number of buses available. The richness and difficulty of this type of problem, has made the vehicle routing an area of intense investigation.

This problem has been largely studied because of the importance of mobility in logistic field. Many different variants of this problem have been formulated to provide a suitable application to a variety of real-world cases, with the development of advanced logistic systems and optimization tools. There are different features that characterize the different variants of this problem.

The problems of allocation of fleet and personnel have been studied and are modelled as classical problems of combinatorial optimization, linear programming, and in many cases are solved in an exact way. The problem of design and optimization of routes and frequencies, by contrast, has been less studied and it is considered as an NP-hard problem. Because the problem is NP-hard to solve it, several heuristic procedures have been proposed in the literature.

The problem is addressed with an approach to combinatorial optimization, which involves in a first formulation of an optimization model and its subsequent resolution algorithm.

It should be noted that the evaluation of the solution involves calculating the objective function of the model and, moreover, the method of resolution must have a compromise between efficiency, measured in time of execution, and quality of the resulting solution. For this reason, when a routing problem is often addressed through the formulation of models whose resolution can be treated using algorithms to optimally solve instances of reasonable size in time.

This work makes a comprehensive analysis of the main models and methods or algorithms that have been used in the literature to address this problem in order to identify similarities and differences between them. Besides, it is possible to study their affinity and opportunities that may present with regard to this case of study.

This paper is organized as follow: In the following paragraph is entered to make a brief overview on the main features of the models and algorithms for optimization of routes and bus frequencies referenced in the literature. For greater simplicity, these features are presented in parameterized variables and are shared by the various proposals and their different approaches or models derived from them and explained in subsequent paragraphs. Finally, conclusions and future work are presented..

2 Models and Algorithms in Optimization of Bus Routes and Frequencies

In general, the optimization of an urban transport system poses collective goals such as: maximize service quality, in terms of minimizing travel times and waiting times, and maximize the benefit of the companies.

The main component that is characteristic of each model is its design, embodied primarily in its objective function. In particular the objective function reflect the interests of users, in this case the passengers, and operators, in this case the transport companies. Then it should be noted that the models presented in this section, in general, seek to maximize the level of service, minimizing resource use, under certain restrictions.

These objectives are generally contradictory, since it implies an improvement in a detriment to other, it is usually required to define a balance between these objectives.

Moreover, it should be noted that the relative importance of components of the objective function is a political decision, therefore, in practice it will usually be defined by regulatory agencies of the system. With regard to it, this paper shows the approach of each of these models and methods and algorithms [8], but the solution proposed in this paper is different because it solves the routes and the buses together, it extends the use of the genetic algorithm and improves some of its operations. For their study the most basic model is taken as a reference, considering similarities of it with the other models and methods.

For the analysis of different models, is necessary to define the characteristics of the problem to be studied and shared by all of them. It is shown in Table 1:

Table 1: Characteristics of the problem to be studied

Variable	Description
n	Number of network nodes
d_{ij}	Demand between the nodes *i* and *j*
t_{ij}	travel time between *i* and *j* (waiting time and transfer time)
t_k	Total travel time of route *k*
N_k	Number of buses operating on route *k*, $N_k = f_k t_k$
f_k	Frequency of buses operating on route *k*
f_{min}	Minimum frequency of buses allowed for the entire bus route
c	Available fleet size (number of buses per hour)
LF_K	Load factor on the route *k*
$(Q_k)_{max}$	Maximum flow for each arc in the path *k*
CAP	Number of seats on buses
LF_{max}	Maximum load factor allowed
R	Set of routes for a given solution
C1, C2	Conversion factors and relative weights of the terms of the objective function
PH_{ij}	Number of passengers per hour between the nodes *i* and *j* (for the travel time of passengers)
WH_{ij}	Waiting time for passengers between the nodes *i* and *j*
EH_r	Empty travel time, which reflects the use of buses
a1, a2, a3	Weights reflecting the relative importance of the terms of the function

Moreover, it should be noted that the algorithms for optimization of routes and frequencies of buses that use these models are based on mathematical programming models solved with approximate methods, heuristics and metaheuristics.

3 Minimizing the Total Time for Transfer Passengers and Fleet Size Required

Through this general pattern that can be used as the basis of the following as outlined in subsequent paragraphs, which provide algorithms for optimization of routes and frequencies of buses [1]. The main aspects of the problem are taken into account, as well as a variety of parameters and constraints (load factor, etc.) [2]. It is flexible because it allows the incorporation of knowledge of users. In this regard, for example, restrictions on minimum cover ratio of demand based on free transfers or travel with at least one transfer can be added when applying a method of resolution.

In this model the components of the objective function are expressed in different units, forcing to the use of conversion factors, as it is shown in equations (1), (2), (3) and (4).

$$\text{Min } C1\sum_{i=1}^{n}\sum_{j=1}^{n} d_{ij}t_{ij} + C2\sum_{k\in R} f_k t_k \quad (1)$$

$$f_k \geq f_{\min} \quad \forall k \in R \tag{2}$$

$$LF_k = \frac{(Q_k)_{\max}}{f_k CAP} \leq LF_{\max} \forall k \in R \tag{3}$$

$$\sum_{k \in R} N_k = \sum_{k \in R} f_k t_k \leq W \tag{4}$$

Method Used: The proposed methodology operates on the basis of the generation, evaluation and improvement of routes. Initially generates a set of routes given the origin-destination matrix as the main guide and found the two shortest paths between a subset of *m* pairs of nodes of high demand, as seen by decreasing its value. It's necessary to specify the demand that can be uncovered is specified. Additional nodes are inserted in the initial skeleton of routes, according to pre-established rules. The generation procedure is repeated, varying parameters, giving solutions to different compromises between objectives.
The main rule to assign the demand is the criterion of minimizing transfers. According to this, for each pair (*i,j*) node checks whether it is possible to travel without transfers, if not possible, alternatives to travel with 1 or 2 transfers are contemplated. Furthermore, the allocation of passenger flows in each arc of the network, and identifies valid frequencies that meet the value of the load factor set. This procedure is repeated until convergence (accepted difference between input and output frequencies of the algorithm). Moreover, the improvement of routes it operates on two distinct levels:

- Coverage of the system, discontinued service at low load of passengers, or with very short routes.
- And, the structure of the routes by combining or dividing routes.

Below are the different variations on this model are:

3.1 First Proposal

The first proposal uses coordinated services planning multimodal transport in heterogeneous fleet mode.
Used as the base heuristic procedures, adding the concept of transfer center (business and employment) [12]. A transfer center is detected based on data production and attraction of trips, and taking into account descriptive metrics of nodes, computed by the evaluation procedure of routes, or manually. Once identified the stops, the routes are constructed and considered. For routes passing through the centers, the frequencies are determined as a multiple of base frequency, to enable coordination between pathways that share transfer centers.

3.2 Second Proposal

In this case, it is necessary an algorithm to generate an initial set of routes based on the shortest path between any pair of nodes and alternative paths.
The routes are checked if they do not comply with certain restrictions (eg, minimum length) and stored as a set of candidate routes [10].
Genetic algorithms are used to select subsets of the set of candidate routes, and is a contribution in the use of metaheuristics in solving the problem.

3.3 Third Proposal

This proposal implies the use of algorithms for the calculation of shortest paths between any pair of nodes in the network, assign demand to check routes and restrictions on minimum and maximum passenger flow arcs.
This procedure identifies the subset of nodes that participate in the process of generating routes. In the generation of initial solutions, it is considered a single objective, to minimize travel times for passengers [11].
k paths are generated between each pair of nodes of high-flow (*k* given by the user) and used genetic algorithms to select from among any pair of *k* nodes. In a second phase will determine the optimal frequency for the solution found in the previous phase. Again using genetic algorithms, where the objective function now incorporates the objectives of the operator, in the form of fleet costs and waiting times at the cost of the user. The main parameter that controls this process is the load factor of buses.

3.4 Fourth Proposal

The last proposal requires the use of Genetic Algorithms.
The proposed methodology requires an initial set of routes (the current collective urban transport system) to be improved. Using genetic algorithms, where the population is pre-cardinality, and each gene corresponds to a line, its value is an allelic pair, the first component indicates the state of the road in that configuration (active or not active) and the second value to their frequency [4].
The approach is similar to that used by the second variant shown above. The particularity of this work is that it uses a neural network to evaluate the objective function. The training of the network is done off-line based on a number of test cases, where each is an allocation process and multi-criteria analysis to determine the value of the objective function.

4 Proposal for Multi-objective Optimization Problem

This model is similar to that proposed above, but is formulated as a multi-objective optimization problem [7] with two objective functions, as they are shown next in equation (5) and (6).

$$\text{Min } Z1 = a1 \sum_{i,j \in N} PH_{ij} + a2 \sum_{i,j \in N} WH_{ij} + a3 \sum_{r \in R} EH_r \quad (5)$$

$$\text{Min } Z2 = W \quad (6)$$

Method Used: It resolves the problems of designing routes and schedules simultaneously, based on the model seen in the previous section, nonlinear mathematical programming with mixed variables, multiple objectives (minimization of travel time and minimizing the size of the fleet) [5]. The model is solved in three phases:

- First, we generate several sets of solutions not dominated by solving a joint problem of coverage.
- Below is an allocation process (not described), which determines the frequencies. For the exploration of alternative solutions using a search method that attempts to avoid local solutions already encountered, so not to start cycles.
- Finally, assess and select the most appropriate alternative, using an adapted method of "programming" for multi-objective optimization.

Its main contributions are: The formal treatment of the problem (by reducing some classic problems as subproblems to the set covering), and the method proposed for identifying non-dominated solutions.

5 Other Proposals

A first proposal is about the use of conversion rates of all components of the objective function: In this model, the formulation is similar to that proposed by the first method above. This model allows calculate frequency of routes, but requires the use of conversion rates to the same unit (cost / time) of all components of the objective function [9]. The objective function is evaluated through an explicit formulation that includes travel time and waiting for passengers and the cost of operating the fleet. The frequencies are determined by minimizing the value of the objective function. The last proposal is about the use of a method using Logit by calculating each line utilities for each origin-destination pair (*i,j*): This model differs from all previous specification of the system components. It proposes an alternative allocation model, which uses the method by calculating logit utility of each line for each origin-destination pair (*i,j*) [6]. Not dealt with issues such as determining the frequency and size of fleet. It requires the use of conversion factors and subjective values of time.

6 Proposal in this Paper: Multi-objective Function. Optimizer in two Levels. Genetic Algorithms

The objective is constructing a tool to support decision making and to complement the knowledge and experience with quantitative elements. The objective is to provide a quality service, previously fixed, with minimal cost to passengers who are at different stops in the different routes. This requires to develop a system of routes and allocation of buses which is optimal in economic terms. Its development is done through a set of procedures or strategies are trying to be simple and effective.

Firstly, this model proposed to consider a multi-objective function, which consists on minimizing the number of buses and minimizing times (waiting time at stops and travel times).

Secondly, this model proposed to consider an optimizer at two levels: selection of routes and assignment of bus to them, because the solution will consist of routes and bus routes.

Besides, the complexity of a real problem of this type has the disadvantage of the many parameters that must be taken into consideration and with the objective that the solution is optimal and in real time. By this, the problem is guided through of a development process into two distinct levels, one to manage the routes and other to manage the allocation of buses on those routes, as it is shown in the next Figure.

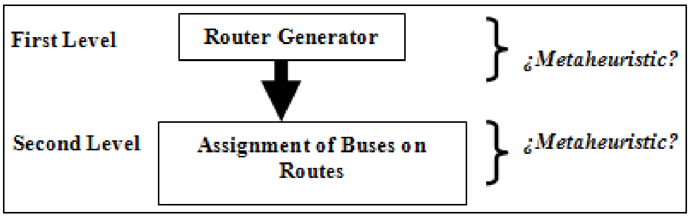


Fig. 1. Resolution proposed for Planning of an Urban Public Transport

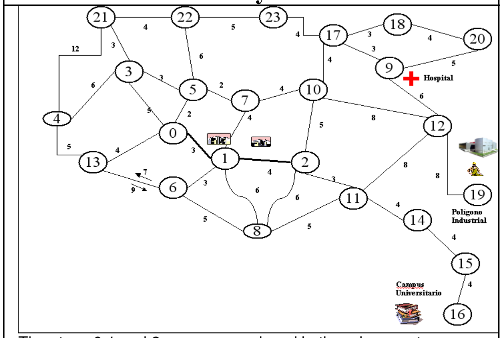
Therefore, the development of a two-level optimizer for solving the proposed problem, constructs a complete solution, comprising a set of routes and a set of buses assigned to them. By this way, the construction of this solution is more refined, to ensure optimality, in two levels, each of them specialized in securing a part of the solution. The joint application of more than one metaheuristic in solving problems of great complexity, leads to build a solution with high security to be optimal.

It has been proposed to apply at each level a Genetic Algorithm, because there are many jobs where this algorithm has proved its effectiveness.

Finally, based on the frequencies obtained for these lines, the user or expert decision-maker may set hours of operation of buses in the city.

Therefore, the process adds a further complexity in the way of solving the problem, but thinks it can ensure greater reliability in the solution thus obtained is optimal. In the next figure, an experimental Session shows the performance of the optimization method proposed in this research:

Entry Data



The stops 0,1 and 2 are narrow, placed in the urban center
Fleet of buses:
2 Short buses and with high platform with capacity of 50 passengers **(Bus of Type 1)**
2 Short buses and with low platform with capacity of 50 passengers **(Bus of Type 2)**
2 Long buses and with high platform with capacity of 100 passengers **(Bus of Type 3)**
2 Long buses and with low platform with capacity of 100 passengers **(Bus of Type 4)**

Solution obtained

Route 1: 1 Bus of the type 2

20	18	17	10
7	5	0	13
13	0	1	6
8	2	10	17
18	20		

Route 2: 1 Bus of the type 1

16	15	14	11
2	1	7	5
22			
22	21	3	5
0	1	2	11
14	15	16	

Route 3: 1 Bus of the type 2

4	13	6	1
7	10	17	9
9	17	10	7
5	3	4	

Route 4: 2 Buses of the type 3 and 2 buses of the type 4

4	3	5	7
10	12	19	
19	12	10	7
5	3	4	

Route 5: 1 Bus of the type 1

8	2	11	12
9	17	23	22
22	21	3	4
0	1	8	

Other results: Demand covered: 76 %, Time of the best solution: 62797 ms, Total time of the algorithm: 123250 ms

Fig. 2. An experimental session of the model proposed in this paper

For a network and certain information of entry there has been achieved an ideal solution formed by a set of routes and the assignment of buses on them, and taking into account that a set of restrictions were satisfied, this solution is, finally, considered as satisfactory to solve this problem.

7 Conclusions

As a summary of the models tested, it should be noted that all of them have a structure with similar characteristics in terms of decision variables, objective function, constraints, and so on. We also have some structural differences in terms of its development in one or two phases, on a single objective or multi-objective regarding the allocation model used.

Finally, it deserves emphasis that these algorithms have the advantage of providing a degree of interactivity to set some parameters and restrictions, are also flexible for its modularity, and allow planning in both the medium and long term [3]. Its main limitation is that it proposes a systematic way of changing the parameters to generate different solutions. There is a trend towards the use of Genetic Algorithms, similar to that occurring in other areas of combinatorial optimization. In contrast with this models analyzed, this paper has proposed an optimization method based in a multi-objective function, an optimizer at two levels and two Genetic Algorithms.

Future work includes using different fuzzy dominance approaches that should be tested to better fit the longest path better. Moreover, this algorithm can be improved with different local search algorithms, to improve the quality of solutions.

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