A Web-based Platform for the Design of Urban Transit Route Networks

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Abstract

The design of public transportation networks requires solving optimization problems, involving various parameters such as the proper mathematical description of networks, the algorithmic approach to apply, and also the consideration of real-world, practical characteristics such as the types of vehicles in the network, the frequencies of routes, demand, possible limitations of route capacities, travel decisions made by passengers, the environmental footprint of the system, the available bus technologies, besides others. The current paper presents the work towards that direction, which employs novel optimization approaches such as the binary particle swarm optimization algorithm. The proposed system employs tiered middleware architectures that integrate geographic information services in order to produce practical, realistic results.

Keywords: *public transport network, environmental optimization, particle swarm optimization, geographic informational systems, middleware*

I. Introduction

The problem of optimizing the use of resources with respect to the environmental impact has been an area of focus during the last decade [1] [2]. The design of a public transportation network is a complex optimization problem, which involves a variety of design parameters (route structure, frequencies, vehicle types, etc.) and assumptions on demand patterns, travel behavior and so on. Indeed, the associated Transit Route Network Design Problem (TRNDP) has been a topic of interest for over 40 years. The combinatorial nature of the TRNDP and the difficulty to formulate it analytically have resulted numerical optimization as the primary means of approaching the solutions over the last years. A review of the recent literature exhibits a variety of relevant techniques

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that consider routes, frequencies and other network parameters, based on preset objective functions, which are to be optimized. Widely used approaches include Genetic Algorithms (GA) [3], Simulated Annealing [4] and Ant Colony Optimization [5] besides others.

The Particle Swarm Optimization (PSO) is one of the most effective evolutionary algorithms inspired from social behavior of animals [6]. Its simplicity and efficiency makes this algorithm very popular. Due to these advantages, the PSO algorithm has been applied to many domains such as medical diagnosis, grid scheduling, robot path planning and computer vision. This algorithm is capable of solving problems with continuous search spaces, while some problems have discrete search spaces. The binary version of PSO (BPSO) was proposed by [7]. The TRNDP belongs to the discrete problems and probably this is the reason that the PSO algorithm has not been applied to this problem so far.

The novelty of the proposed approach is the formulation of the TRNDP problem in a way that is solvable by the BPSO optimization method. This way we are able to exploit the good features of this very powerful algorithm. Furthermore, we have exploited the Google maps API to visualize our results.

The rest of the paper presents the formulation of the TRNDP problem so that PSO optimization procedures can be used to approach its solution. The paper is structured as follows: section 2 analyses the formulation of the problem. Section 3 describes the component architecture of the proposed framework. Section 4 presents the conclusions of this work and the future perspective.

II. Problem formulation

This work has been based on the assumptions that there is a fixed number of S bus stops, a fixed number of bus lines L and that the bus lines have a maximum number of s bus stops.

The solution is represented by a binary two dimensional matrix of L rows and s columns. The l-th row represents the l-th bus line. A "1" in position (l, σ) represents that the l-th bus line goes through the σ-th bus stop, while a "0" represents that the bus line does not include the bus stop. The solution must be in vector form, therefore, we vectorize the 2D matrix to formulate the hereafter mentioned as "LN" vector with $L \times s$ elements. To the previous vector we also have to append bits to encode bus frequencies per line (number of bits depends on what is the maximum bus frequency) hereafter denoted as "f" and whether the line is operated by electric or conventional bus hereafter denoted as "G".

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Having available the solution in a binary form we seek to minimize the objective function given by:

$$\begin{aligned} min Z &= w_1 D_u(\bar{L}\bar{N},\bar{f}) + w_2 T(\bar{L}\bar{N},\bar{f}) \\ &+ w_3 e(\bar{L}\bar{N},\bar{f},\bar{G}) + w_3 N_{cs}(\bar{G}) + w_5 V_c(\bar{L}\bar{N},\bar{f},\bar{G}) + \\ & w_6 D_e(\bar{L}\bar{N},\bar{f},\bar{G}) \end{aligned} \quad (1)$$

where *Du* is the unsatisfied passenger demand (traffic associated to stops not served under maximum number of transfers), *T* the average travel time, *e* the pollution emissions *N*cs the number of charging stations, *Vc* the required number of conventional vehicles and *Ve* the required number of electric vehicles. The weights w1 - w6 are defined according to the policy we want to implement or according to values that can be statistically estimated. All the above quantities are straightforward to compute given *LN*, *f*, *G*.

However, the question that the proposed formulation leaves open is: given the solution vector how do we define the sequence of the bus stops? Clearly the solution vector does not really capture the sequence in which the bus stops are visited. This is done deliberately and is one of our major contributions, because we significantly reduce the solution space. E.g. for $S = 50$ and $s = 10$ the number of possible permutations in which we are seeking optimum is ~1016, while if we ignore the permutations as in our method this reduces the search space to ~1011, which is a very significant reduction.

The answer is given by assuming that the next bus stop is the one closest to the current one. In other words we need to define the path that covers all the bus stops and at the same time has the minimum possible length. The answer to this problem is given by solving the traveling salesman problem, which solves exactly this problem [8]. This problem is NP-hard and solved by using genetic algorithms or a PSO method as well.

III. The Binary PSO Algorithm

The binary version of PSO (BPSO) was proposed by [7]. The continuous and binary versions of PSO are distinguished by two different components: the transfer function and the different position updating procedure. The transfer function is used to map a continuous search space to a binary one, and the updating process is designed to switch positions of particles between 0 and 1 in binary search spaces. Several solutions have been proposed to the problem of getting trapped in local minima, e.g., [10], [11]. In [12], two different families of transfer functions, v- shaped and s-shaped were investigated. Let's start from the continuous PSO. Each particle *i* at time *t* corresponds to a single solution *xi(t)*. To evolve towards a better solution the particle has to consider the current position, the current velocity *vi*(*t*), the distance to their personal best solution, *pbest*, and the distance to the global best solution, *gbest*. This is formulated as follows:

$$v_i(t+1) = w*v_i(t) + c_1*r_1*(pbest - x_i(t)) + c_2*r_2*(gbest - x_i(t)) \quad (2)$$

where w is a weighting function, $r1$, $r2 \in [0,1]$ are random numbers and $c1$, $c2$ are acceleration coefficients. In the next iteration the particle will evolve to:

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (3)$$

In binary space, due to dealing with only two numbers (‘‘0’’ and ‘‘1’’), the position updating process cannot be performed using eq. (3). Therefore, another definition of velocities is needed for changing positions from ‘‘0’’ to ‘‘1’’ or vice versa. This can be done by redefining the velocity to be the probability of a bit taking the value 0 or 1. A sigmoid transfer function as in eq. (4) was employed in [1] to transform all real values of velocities to probability values in the interval [0,1].

$$T(v_i^k(t)) = \frac{1}{1 + e^{-v_i^k(t)}} \quad (4)$$

where *vi k(t)* indicates the *k*-th dimension of the velocity vector. Then the position vectors are updated according to the following:

$$x_i^k(t+1) = \begin{cases} 0, & if \ r < T(v_i^k(t+1)) \\ 1, & if \ r \geq T(v_i^k(t+1)) \end{cases} \quad (5)$$

where r is a random number in the interval [0, 1]. Variations of this strategy have been proposed in [10], [11], [12].

In this work the TRNDP problem is solved by using the BPSO method since it is an NP-hard problem, which requires a sub-optimal solution.

IV. Implementation and Experimental Results

The design of our case study is based on the combination of presentation technologies, middleware and computational analysis, namely: HTML, Javascript, Google Maps API at the presentation tier, Hypertext Preprocessor (PHP), the known dynamic programming language for the middleware and Octave / Matlab for the computational analysis back-end. More specifically, the systems includes a graphical web interface capable of displaying the graph of the problem realistically and in real time through the programming interface of Google Maps engine management. The graph presented by Google Maps is processed by means of a computational analysis module which implements the TRNDP solver based on the Octave and Matlab environments. Middleware logic, is capable to handle requests directed towards the graphical interface,

direct them to the computational analysis module and return results in appropriate form to be presented by the maps presentation engine.

The Google Maps map management and presentation engine offers programming interfaces that are compatible with various programming languages. For the purposes of our work, we took advantage of the JavaScript programming [9]. Necessary conditions for the use of the interface has been the knowledge of web technologies and principles of object-oriented programming design mode. This platform was chosen because it dominates the market of GIS and provides free, stable and reliable access. Google maps also offer interesting features such as real time traffic support, carbon dioxide emissions estimations, beside others, which may be exploited by our system in the future. The use of the programming interfaces of the platform service is offered by means of subscription and the acquisition of appropriate application programming interface (API) keys that allow the service to monitor usage. Typical facilities include the *Distance Matrix Service* offering distance calculation service between start and destination nodes, *Directions Service* offering directional calculation service between one or more locations, *Directions Route* service offering route calculation between departure and destination which contains the sections of the route, among others, Map objects capable to illustrate maps. Features of the service include vehicle type specification, travel modes that is bicycling, driving, transit, or walking.

As a commercial product, the Google Maps API allows limited use when not in subscription mode. In this context the design of our system took into account the respective restrictions. When the design took place the former allowed 25,000 map loads per day for 90 consecutive days, recovering 100 elements each performed search (query), recovering 100 elements per 10 seconds, recovery of 2,500 items per 24 hours. It is worth noting that requests are also subject to rate limits. The design of the system took into account all the above restrictions in order for the system to be capable to represent nodes (stops) as points in Google Maps, represent of realistic routes, i.e., routes that take account of actual characteristics as, e.g., one-way (see Fig. 1).

GNU Octave is a high-level programming language, primarily intended for numerical computations. It offers a command line interface for solving linear and nonlinear problems numerically, and for performing other numerical experiments using an interpreted language mostly compatible with the well-known MATLAB platform by Mathworks. It can also be used as a language oriented script execution. Octave is free software, distributed under the terms of the GNU General Public License. It is written in C ++ and uses the standard C ++ library, it uses an interpreter to execute the script language and it is expandable with the use of dynamic parts (modules). The architecture of our solution employs open source PSO packages compatible with Octave.

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The architectural components and their integration was a challenge for the implementation of the system. Google maps was a valuable and suitable solution since it offers unique functionality, satisfactory front-end interface and sufficient, usable APIs. Matlab is both capable and efficient to execute the algorithmic logic but, by design, not suitable for the middle tier of the platform; Octave on the contrary is very easy to integrate but does not support either PSO or genetic algorithms to the desirable extent, which we had to implement from scratch. In order to produce realistic, applicable solutions the system needs to produce meaningful routes; to this end they needed to be optimized with respect to their total distance. Thus, besides optimizing with respect to the objective function analyzed above, it was decided to recover the shortest possible route that visits each node exactly once and returns to the origin. The aforementioned sentence is an expression of the Traveling Salesman problem [13] the well-known non-deterministic polynomial time NP-hard problem. This logic also needed to run in the middle tier.

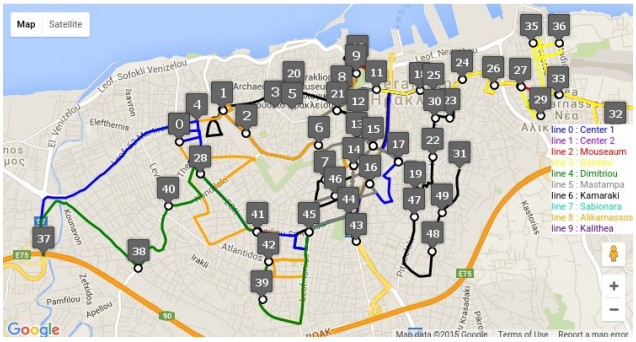

Figure 1: A snapshot of the system output based on the Google Maps platform.

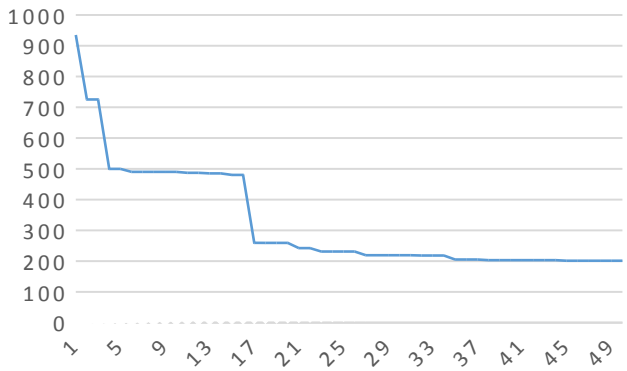

Figure 2: Snapshot of the minimization process of the objective function based on the best particle. The y-axis is the objective value and the x-axis is the iteration number.

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In our preliminary experiments, running the BPSO method in comparison to a genetic algorithm and using the same objective function and an identical formulation of the solution vector, the BPSO converged approximately 20-25% faster for the same population size and gave on average better optimal solutions to the objective function.

The proposed formulation gave convergence that would vary between 1.5-2 hours for 50 bus stops and 5 different bus routes using a population of 1500 particles. A snapshot of the minimization process is given in figure 2. An alternative implementation with a genetic algorithm, which would try to encode in the solution vector the bus stop sequence, e.g., as in [3] had to run for several days, which was a motivation for us to reformulate the solution vector.

V. Conclusions and Future Work

The current paper outlines the design of a web-enabled system that is capable of solving the TRNDP problem using an evolutionary PSO approach. The objective function of the optimization algorithm is very similar to [3]; it ultimately aims to produce solutions that optimize environmental parameters that is, vehicle emissions and vehicle types (electrical or conventional) besides more typical parameters of the problem such as distances, bus frequencies, demand. The design is innovative since the formulation of the solution is binary, designed to facilitate the BSPSO algorithm. Also, the architecture of the informational system is designed to interact with well-known GIS services, relies on middleware logic that executes the optimization and presents the results using web technologies. The implementation relies in platform independent server-side logic that can be called by any component of the system.

We have produced some experimental results that exhibit realistic solutions for the case of Heraklion, Crete. In the next steps we will try to store the results of the traveling salesman problem in a form so that they do not have to be calculated on the fly, in a form that will be easy to retrieve. We also plan to do extensive experimental evaluation and comparisons to other algorithms for a series of cities as well.

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