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Tabu-based GIS for solving the vehicle routing problem

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ABSTRACT

Besides being a hard combinatorial problem, the VRP is also a spatial problem. Hence, effective decision making in this field strongly requires the integration of GIS and optimization systems (GIS-O). This article integrates GIS and optimization tools for solving the vehicle routing problem with loading and distance requirements (DCVRP). A general outline of the multi-step integration is pointed out showing the interaction of the GIS and the spatial optimization according to the loose coupling strategy. The computational performance of the TS-VRP algorithm for the DCVRP turned out to be quite efficient on both computation time and solution quality. The Tunisian case study well illustrates the incentive behind using such a spatial decision support system that allows the management of the problem from the data acquisition to the visualization of possible simulation scenarios in a more realistic way.

1. Introduction

GIS is getting pride of place in addressing strategic applications where data are structured as multi-layered records in the database. GIS also offer numerous functionalities as collecting, analyzing and displaying data. It has proven its efficiency in various areas of study by solving different kinds of problems in several application domains which made it so popular and widespread. However, the future of GIS is full of challenges. One big challenge is the complex nature of some strategic problems that GIS must deal with, it often shows its limitations. To avoid such situations, the use of GIS must be consolidated. Optimization offers various tools that can widely contribute to improving the GIS performance while tackling and solving more complicated problems (Li, Chen, Liu, Li, & He, 2011) as well as in the multicriteria decision making (Malczewski, 2006).

This paper takes place in the framework of integrating two systems belonging to different areas of study in order to strengthen the efficiency of the whole system. As we are addressing the integration of a GIS and an optimization tool, we call such system a "GIS-O" that can operate with respect to various integration protocols. The overview of GIS-O covers three main classes of integration strategies revealed by the literature namely the full, the loose and the tight integration strategies. A close analysis as the one performed by Faiz and Krichen (2013) shows that selecting the appropriate strategy is application dependant. Among the wide spectrum of domains that might be linked to GIS, our special attention is dedicated to the class of transportation problems, particularly to the vehicle routing problem (VRP) for being a relevant issue to both combinatorial optimization and distribution management.

To this end, we propose a loose integration approach, designed as a spatial decision support system (SDSS) that manages the data from the geographical database (GDB) and solves the obtained problem to be later plotted on the map. Deciding for the loose integration approach to build a GIS-O software is motivated by the independence of the linked systems resulting in a reduced cost and a low integration time. Moreover, it is recommended for its considerable flexibility promoting the free selection of models to be combined and their exchangeability when required. Specifically, the loose integration approach starts by extracting distances between each pair of points from the GDB, then computing the cost matrix and other additional details about the vehicles. All such data constitute inputs for the optimization step used to generate a routing plan which will be visualized in a cartographic format showing, for each vehicle, the itinerary to be followed corresponding to a cost saving solution.

The contributions of this research are several. This paper proposes a SDSS for an important VRP variant often present in real-life applications called the distance-constrained capacitated vehicle routing problem (DCVRP). When solving such complex problems, the quality of the generated solutions depends closely

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on the problem size, allowing the use of either an exact or an approximate method. In this work, small scaled instances are solved using the CPLEX optimizer, whereas, larger instances require an approximate approach as the tabu search (TS) metaheuristic, known as a powerful method for generating high quality solutions in the transportation context (Cordeau, Gendreau, Laporte, Potvin, & Semet, 2002). The computational results show that the proposed TS method is effective for solving the CVRP. Compared to other state-of-the-art approaches, the TS is quite competitive and it is faster than the other methods.

Illustrations of the SDSS address two main applications: The first one is related to an urban area called Ezzahra, a town in the north of Tunisia, on which 15 customers are to be served by means of at most 4 vehicles. As the corresponding DCVRP is small scaled, the SDSS performs its CPLEX component to generate an optimal solution. The second application referring to the whole cartographic map of Tunisia is a large sized DCVRP that involves 100 customers to be supplied from the depot using 15 available vehicles. In this case, the SDSS performs the TS metaheuristic and provides a sub-optimal solution in a reasonable computational time. Such illustrations show that the proposed DCVRP loose integration performs well in both the quality and the ease-of-use for a rational decision making process.

The remainder of this paper is structured as follows. In Section 2, we provide the background information of spatial decision support systems. In Section 3, we describe in detail the DCVRP. In Section 4, we develop a SDSS based on a GIS-O loose integration of QGIS and CLPEX-TS. Section 5 shows the capabilities of the GIS-O loose integration in handling two real case studies. Conclusions are reported in the final section.

2. Problem background

The way of addressing the VRP has seen major changes from the 1960s to this date. Starting with non-computerized methods where vehicle routes were designed manually on paper maps, these methods were revolutionized by introducing routing heuristics capable of solving larger problems more efficiently. Afterwards, linking optimization techniques to database management systems along with providing visual interfaces gave rise to vehicle routing systems (VRS) which are considered as decision support systems (DSS) for effective decision making (Igbaria, Sprague, Basnet, & Foulds, 1996).

As research in the field of the VRP is being accumulated, a major shortcoming of vehicle routing systems has been identified. By nature, the VRP has an obvious spatial dimension which is often neglected by traditional VRS (Keenan, 1998). More recently, a generalized version of the VRP was proposed by Pop, Matei, and Valean (2011, 2013), that is a natural extension of the basic VRP where there is a set of clusters to refer the constraints of feasibility.

Hence, handling geographic and spatially referenced data is becoming an urgent necessity to provide efficient routing solutions. The most promising solution to handle spatial data is doubtlessly the GIS. In fact, considering GIS as an opportunity to optimize VRS can be viewed as a new trend in solving routing problems that emerged as a result of the remarkable successes achieved by GIS in various domains (Rossi, Ferrarini, & Parolo, 2009; Schaumann, Funke, & Schultz, 2000).

However, traditional GIS could not support efficiently vehicle routing since it provides only a limited number of routines for finding shortest paths. Therefore, GIS brings only a part of the solution to the inefficiency of routing DSS in handling spatial data. A promising solution described and discussed by many authors (Chen, Pea-Mora, & Ouyang, 2011; Crossland, Wynne, & Perkins, 1995; Gayialis & Tatsiopoulos, 2004; Li et al., 2011) consists of developing a spatial decision support system (SDSS). It aims to efficiently link GIS and optimized routing techniques so that spatial data handling serves at best hard-constrained VRPs.

Table 1 highlights the main differences between a traditional vehicle routing DSS and GIS in dealing with the VRP and shows how a SDSS can benefit from strengths of both systems while avoiding their shortcomings.

2.1. Integration of GIS and vehicle routing systems

The most challenging issue while designing a SDSS is how to perform the integration process. Following the general schema of integrating GIS and optimization systems, the same three main coupling strategies can be adapted to develop such SDSS namely, the loose, tight and full as illustrated by Fig. 1:

- *Full integration strategy:* It consists of fully embedding vehicle routines into the GIS software using its macro language or other advanced languages. The DM takes full advantage of GIS strengths in terms of spatial database, analysis and visualization while added components optimizes vehicle routes (Bodin & Levy, 1994).
- *Loose integration strategy:* GIS and VRS are kept separate but communicate through exchanging data files. The DM benefits from database and visualization tools of GIS as well as all possible optimization techniques made available by a VRS.
- *Tight integration strategy:* Most needed routines are encompassed in the GIS software (full integration) while less utilized ones are kept in the VRS (loose integration). The DM experiences the comfortable feeling of dealing with a well integrated system through a common GUI and a common data storage (Chen et al., 2011).

Selecting appropriate approaches for integration is problem-dependant. Several determinant factors such as level of integration, integration cost, required time and user expertise should be carefully considered while choosing the best coupling approach for a specific problem that complies with DM's expectations.

2.2. Advantages and benefits of using a SDSS

Coupling GIS and VRS in the context of SDSS turned out to be extremely advantageous while tackling practical and real-life applications without further complicating the GIS software or the VRS. We state below the main benefits from developing a GIS-based decision support system for the VRP (Crossland et al., 1995, Tarantilis & Kiranoudis, 2002, Tarantilis, Diakoulaki, & Kiranoudis, 2004).

2.2.1. Reduced routing costs

Computation performance of the optimization algorithm along with accurate and updated spatial data provided by the GIS results in generating high quality routing solutions. Minimizing travel time implies the possibility of including more customers in existing vehicle routes. Hence, utilization of the company fleet is improved, fixed costs of vehicles are reduced and the number of hired drivers is minimized.

2.2.2. Easier redesign of vehicle routes

The decision maker is allowed to dynamically introduce changes on the established routing plan generally caused by customer emergent demands, customer cancelation demands or unpredicted vehicle damages. In such cases, the routes are redesigned and the optimality of the resulted routing plan is constantly checked.