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Discrete Optimization

A unified solution framework for multi-attribute vehicle routing problems ☆

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ABSTRACT

Vehicle routing attributes are extra characteristics and decisions that complement the academic problem formulations and aim to properly account for real-life application needs. Hundreds of methods have been introduced in recent years for specific attributes, but the development of a single, general-purpose algorithm, which is both efficient and applicable to a wide family of variants remains a considerable challenge. Yet, such a development is critical for understanding the proper impact of attributes on resolution approaches, and to answer the needs of actual applications. This paper contributes towards addressing these challenges with a component-based design for heuristics, targeting multi-attribute vehicle routing problems, and an efficient general-purpose solver. The proposed Unified Hybrid Genetic Search metaheuristic relies on problem-independent unified local search, genetic operators, and advanced diversity management methods. Problem specifics are confined to a limited part of the method and are addressed by means of assignment, sequencing, and route-evaluation components, which are automatically selected and adapted and provide the fundamental operators to manage attribute specificities. Extensive computational experiments on 29 prominent vehicle routing variants, 42 benchmark instance sets and overall 1099 instances, demonstrate the remarkable performance of the method which matches or outperforms the current state-of-the-art problem-tailored algorithms. Thus, generality does not necessarily go against efficiency for these problem classes.

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1. Introduction

General-purpose solvers for combinatorial optimization are algorithms that can be used to address large classes of problem settings without requiring extensive adaptations, user involvement or expertise. The development of such solvers is critical to the understanding of the impact of problem characteristics on the performance of solution methods, as well as to the capability to efficiently address new problem settings and applications displaying particular sets of characteristic combinations. One thus aims for high-performance general-purpose solvers, achieving a subtle balance between generality of scope and specificity in exploiting particular problem characteristics, to identify high-quality solutions for the broadest set of problem settings possible within limited computation time. Such developments are very challenging. As illustrated by Wolpert (1997), generality may be paid for in terms of performance, while dedicated algorithms cannot address problem variants without extensive adaptation.

We focus on vehicle routing problems (VRPs), one of the major classes of combinatorial optimization problems with an extremely broad range of applications. Real-life settings lead to a very large number of variants born of the requirement to manage a wide variety of characteristics and decisions, called *attributes* in Vidal, Crainic, Gendreau, and Prins (2013b), to account for the particular customer, vehicle, driver, and network settings and to combine routing considerations with other tactical or strategic choices. The number of VRP attributes that need to be jointly considered is continuously increasing, yielding a considerable variety of *Multi-Attribute Vehicle Routing Problems* (*MAVRPs*).

The current state-of-the-art and knowledge does not offer the means to use exact solution methods for combinatorial optimization as general-purpose solvers for MAVRPs. Consequently, literally hundreds of papers were published recently, proposing supposedly

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☆ An Electronic Companion has been submitted with the paper. The EC can also be downloaded from http://w1.cirrelt.ca/~vidalt/en/VRP-resources.html.

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different heuristic methods for VRP variants with diverse combinations of sets of attributes. As for the most general vehicle routing metaheuristics proposed in the literature (Cordeau, Gendreau, & Laporte, 1997; Cordeau, Laporte, & Mercier, 2001; Ropke & Pisinger, 2006a; Ropke & Pisinger, 2006b; Subramanian, Uchoa, & Ochi, 2013), they usually address a single difficult compound problem formulation including several variants as special cases, but still require extensive adaptation when the main problem setting is modified. The field thus lacks an efficient general-purpose MAVRP solver, and building one represents a considerable research challenge. Our objective is to address this challenge and propose a component-based heuristic framework and a general-purpose solver providing high performance in terms of solution quality and computational efficiency for a very broad and diverse set of multi-attribute vehicle routing problems. These new contributions may point to promising developments in related fields such as scheduling.

We thus introduce a component-based heuristic solution framework designed in accordance with problem structure and attribute specifics, as well as a Unified Hybrid Genetic Search (UHGS). Any unified method must ultimately account for the specific attributes, objectives, and constraints of the particular problem setting at hand. Yet, to achieve a high level of generality, these problem attributes are confined to restricted adaptive components. Thus, UHGS relies on unified problem-independent procedures: local search, crossover, Split algorithm and diversity management, while problem-specific strategies are restricted to a few modular components which take charge of assignment changes (e.g., of customers to depots or days), enumerations of sequencing alternatives, and route evaluations. These components are self-adapted in relation to the attributes of the problem at hand. Furthermore, to achieve high efficiency during local-improvement procedures, we propose a unified route-evaluation methodology based on information preprocessing on sub-sequences, and move evaluations as a concatenation of known sub-sequences. This framework unifies and extends efficient pre-processing techniques which were previously used for different problems.

Extensive computational experiments demonstrate the remarkable performance of the resulting metaheuristic on the classical VRP as well as on MAVRP with multiple periods, multiple depots, vehicle-site dependencies, soft, multiple, and general time windows, backhauls, cumulative or load-dependent costs, simultaneous or mixed pickup and delivery, fleet mix, time dependency, service site choice, driving and working hours regulations, and many of their combinations. With a single implementation, parameter setting and termination criterion, UHGS matches or outperforms all current problem-tailored methods, from more than 180 articles, on 29 vehicle routing variants, 42 benchmark sets and a total of 1099 problem instances. Hence, it appears that generality does not necessarily impede efficiency for the considered problem classes.

The contributions of this work are the following: (1) A component-based heuristic design is proposed for multi-attribute vehicle routing problems, which efficiently isolates problem-specific adaptations from the generic framework; (2) A unified framework for efficient route evaluations and local search, based on efficient move-evaluation techniques from Kindervater and Savelsbergh (1997), Savelsbergh (1985), Savelsbergh (1992), which builds and exploits information on sub-sequences through concatenation operations to efficiently explore neighborhoods; (3) Unified versions of efficient genetic operators, solution representation, and *Split* algorithm; (4) A UHGS which addresses a large set of variants with a single implementation and set of parameters, and yields solutions of exceptional quality on prominent VRP variants and benchmark instance sets.

This paper is structured as follows. Section 2 states the problem, reviews the main classes of general-purpose MAVRP solvers, and introduces the proposed component-based heuristic design. Section 3 details the unified local search and route-evaluation operators. Section 4 describes the UHGS. Computational experiments on a wide range of problems are reported in Section 5. Section 6 concludes.

2. Problem statement and general methodology

Vehicle routing problems have been studied for more than 50 years, serving as support for a vast literature, including numerous surveys (see Andersson, Hoff, Christiansen, Hasle, & Lokketangen, 2010; Gendreau, Potvin, Bräysy, Hasle, & Lokketangen, 2008; Vidal et al., 2013b, among others), books (Golden et al., 2008; Toth & Vigo, 2002), and overall more than a thousand dedicated journal articles (Eksioglu, Vural, & Reisman, 2009). The research effort on the topic is still growing today, because of its major economic impact, the large difficulty of many settings, and the considerable variety of attributes combinations encountered in practice.

2.1. Vehicle routing problems, notations and attributes

The classical Capacitated Vehicle Routing Problem (CVRP) can be stated as follows. Let $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ be a complete undirected graph with $|\mathcal{V}| = n + 1$ vertices, vertex $v_0 \in \mathcal{V}$ representing a depot, where a fleet of m identical vehicles with capacity Q is based, the other vertices $v_i \in \mathcal{V} \setminus \{v_0\}$ for $i \in \{1, \ldots, n\}$ representing customers characterized by a demand for q_i units of product. Edges $(i, j) \in \mathcal{E}$ illustrate the possibility to travel from a customer v_i to a customer v_j for a cost d_{ij} (assimilated to the distance). The CVRP requires designing up to m cycles (vehicle routes) starting and ending at a depot v_0 in order to service each customer once.

Many VRP variants with *attributes* have emerged due to the requirements of practical applications. These particular versions aim at better accounting for customer requirements (e.g., time-dependent service costs, time windows, multiple planning periods), network and vehicle characteristics (multiple depots, congestion, heterogeneous fleet, vehicle-site dependencies), driver needs (working hour regulations, lunch breaks), or at better integrating the decisions in a tactical or strategic planning (inventory or location routing). The large variety of actual settings, characteristics and VRP attributes is addressed by a vast literature. For the sake of conciseness, a detailed literature review on all considered VRP variants is out of scope. Comprehensive surveys can be found in Gendreau et al. (2008), Golden et al. (2008), Andersson et al. (2010), and Vidal et al. (2013b).

As in Vidal et al. (2013b), three main categories of attributes are discerned in this paper. ASSIGN attributes are problem particularities requiring decisions on the assignment of customers to some globally constrained ASSIGN Attribute Resources (AARs), for example, depots, days or vehicle types. Notice that “Profits” is defined as an ASSIGN attribute. Indeed, VRP with profits lead to an assignment of customers to two mutually exclusive groups, customers selected for service and the ones which are not. Routing costs are in this case dependent upon the AAR. SEQ attributes are problem characteristics that explicitly impact the structure and geometry of the routes such as, backhaul trips, multiple trips, or multi-echelon attributes. Finally, EVAL attributes affect the way routes are evaluated. This latter class of attributes encompasses advanced route costs or feasibility evaluations, as well as the eventual optimization of additional decisions on routes (e.g., service dates, waiting times, packing of objects in the vehicle) when the

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