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Iterated greedy heuristic for the time-dependent prize-collecting arc routing problem

Vincent F. Yu [a], Shih-Wei Lin [b,*]

[a] Department of Industrial Management, National Taiwan University of Science and Technology, Taiwan
[b] Department of Information Management, Chang Gung University, Taiwan

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ABSTRACT

The time-dependent prize-collecting arc routing problem (TD-PARP) determines a number of full truck-load orders and plans a vehicle route to maximize profit, which is calculated as total collected revenue (prizes) minus total travel cost. The travel cost on an arc is proportional to the travel time via the arc and changes over time. This study proposes an iterated greedy (*IG*) heuristic for the TD-PARP. Computational study on 41 benchmark problems indicates that the proposed *IG* heuristic outperforms existing approaches. The proposed *IG* heuristic obtains the best solutions to most of the benchmark problems.

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1. Introduction

In full truck load transportation, transport managers may need to select a number of potential orders, each of which involves an origin point and a destination point of freight, and plan a vehicle route to fulfill orders to maximize profit which is calculated as total revenue (prizes) collected from the orders minus total travel costs. The service vehicle leaves the depot, fulfills selected orders, and then returns to the depot. This problem can be modeled as the prize-collecting arc routing problem (PARP) on a directed multi-graph, where each arc is associated with a cost proportional to the travel time/distance on the arc. Some arcs are prize arcs, each associated with a nonnegative prize representing order revenue. One of the nodes corresponds to the depot and the others represent freight origins and destinations. It is assumed that there is at least one directed arc links the freight origin and destination. Parallel arcs are allowed to represent multiple orders between the same pair of origin and destination. For practical reasons, the literature proposes many different versions of PARP which will be discussed in Section 2.

In real-world applications, traffic conditions change during the day and impact the results of original route planning. Using the traffic information in route planning can provide a more accurate estimate of the travel time between each pair of nodes, and thus a more realistic route plan. Therefore, Black, Eglese, and Wohlk (2013) proposed the time-dependent prize-collecting arc routing problem (TD-PARP) to consider the predetermined time-dependent travel time.

More formally, the TD-PARP can be defined on a directed multi-graph $G = (V, A)$ where V is the set of nodes, one of which is designated as the depot and A is the set of arcs connecting nodes. Let $P \subseteq A$ be the set of prize arcs. Each arc $r = (i, j) \in P$ is associated with a nonnegative prize p_r, which is collected on the traverse of arc r. For each arc $(i, j) \in A$, $f_t(i, j)$ represents the nonnegative time-dependent travel time required to travel from node i to node j when leaving node i at time t. The aim of TD-PARP is to design a single vehicle route that maximizes profit (total collected prizes minus vehicle travel cost). The vehicle leaves the depot at time $T_{\min}$ and must return to the depot no later than time $T_{\max}$. Waiting at any node is not permitted. Black et al. (2013) proposed a mathematical model for TD-PARP.

Black et al. (2013) observed that the best TD-PARP solutions obtained from 10 one-minute runs are better than those obtained by one 10-min run. This implies that, at least for their algorithm, quickly exploring a large number of diversified solutions may be more effective in solving TD-PARP. The iterative greedy (*IG*) heuristic proposed by Jacobs and Brusco (1995) is one of such solution methods. Both conceptually and practically, it is one of the simplest meta-heuristics, and has been applied successfully to many hard combinatorial optimization problems (Lin & Ying, 2014). This study thus proposes an iterative greedy (*IG*) heuristic to solve the TD-PARP. *IG* heuristic has been applied to many scheduling problems (Deng & Gu, 2014; Ding et al., 2015;

* Corresponding author.
E-mail address: swlin@mail.cgu.edu.tw (S.-W. Lin).

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Fernandez-Viagas & Framinan, 2015; Lin, Ying, & Hwang, 2013; Pan & Ruiz, 2014; Rodriguez, Lozano, Blum, & García-Martínez, 2013; Tasgetiren, Pan, Suganthan, & Buyukdagli, 2013). It has also been used to solve the traveling salesman problem with time windows (Karabulut & Fatih Tasgetiren, 2014). To our best knowledge, this study is the first to apply *IG* heuristic to arc routing related problems. To enhance the performance of the *IG* heuristic, we also developed two variants of the *IG* heuristic in which exchange-based local search methods are applied. The proposed heuristics are tested on a set of benchmark problems generated by Black et al. (2013). Computational study indicates that the proposed *IG* heuristics are comparable with existing approaches.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 provides technical details of the proposed *IG* heuristic and its implementation. Computational results are reported in Section 4, followed by conclusions in Section 5.

2. Literature review

The prize-collecting arc routing problem was introduced by Malandraki and Daskin (1992) as a practical extension to the Chinese Postman Problem. They considered the problem on a directed network and proposed a branch-and-bound algorithm for the problem. Subsequently, Pearn and Wang (2003) studied the same problem but on an undirected network. They proposed a heuristic algorithm that applied minimal spanning tree and matching algorithms on an expanded network to solve the problem. Feillet, Dejax, and Gendreau (2005) considered a similar problem on a directed network called the profitable arc tour problem which considered multiple vehicles and an additional route duration constraint. They proposed a branch-and-price algorithm to solve the problem.

The three studies mentioned above all assumed that the prize on an arc can be collected multiple times. Aráoz, Fernández, and Zoltan (2006) defined a similar problem called Privatized Rural Postman Problem in which the prize on an arc can be collected only once. They showed that the problem is NP-hard and studied the polyhedral properties of the problem. Aráoz, Fernández, and Meza (2009) studied the same problem and proposed a two-phase method for the problem based on constraint relaxations, that is, only a subset of constraints were considered.

Franquesa (2008) defined the Clustered Price-collecting Arc Routing Problem in which prize arcs are clustered and the vehicle must traverse all prize arcs in a cluster if any one of the prize arcs in the cluster is visited. Aráoz, Fernández, and Franquesa (2009) presented a branch-and-cut algorithm for the problem. Corberán, Fernández, Franquesa, and Sanchis (2011) studied the same problem with asymmetric costs on the arcs called the Windy Clustered Prize-collecting Arc Routing Problem. They presented a mathematical programming model and a cut-and-branch algorithm for the problem.

Archetti, Feillet, Hertz, and Speranza (2010) considered a capacitated version of the PARP with a different objective function. Each arc is associated with a demand and a prize. A fleet of capacitated vehicles is used to fulfill the demands and collect prizes on prize arcs. The prize on an arc can be collected at most once and route duration constraint is imposed. The objective is to maximize the collected prize instead of the profit. They proposed a branch-and-price algorithm and several meta-heuristics to solve the problem. Zachariadis and Kiranoudis (2011) studied the same problem with two objectives. The first goal is to maximize the collected prizes while the second is to minimize the total travel cost. They proposed a local search heuristic for the problem.

Black et al. (2013) provided a comprehensive review of the literature on PARP. They classified the PARP variants in the literature based on several problem characteristics including the number of vehicles used (single or multiple), number of collections permitted from a prize arc (once or multiple times), upper bound on the total travel time or cost, vehicle capacity constraint, clustering constraint, and network type (directed or undirected).

Traffic conditions change with time of a day, and thus travel time between two points may vary from time to time. This phenomenon is more apparent in urban areas and impacts the results of the traditional vehicle routing models that assume constant travel time from an origin to a destination. Ignoring time-dependent travel time in route planning may result in inefficient and suboptimal solutions, especially in urban areas (Figliozzi, 2012). Therefore, recently many researchers have attempted to develop time-dependent versions of existing routing models. Consequently, many routing models that incorporate time-dependent travel times have been proposed and attracted attention from both academia and industry.

Black et al. (2013) were the first to propose the time dependent prize-collecting arc routing problem to consider the variance in travel time during the planning horizon. They presented a mathematical model for the problem and proposed two meta-heuristics for the TD-PARP. The first one is tailored for the TD-PARP based on variable neighborhood search (*VNS*), while the second is modified from the *LANTIME* heuristic proposed by Maden, Eglese, and Black (2010) for the time-dependent vehicle routing problem.

3. The proposed iterated greedy based heuristic

A generic *IG* heuristic generally begins from an initial solution π_0 and generates a sequence of solutions by iterating through the *destruction* and *construction* phases (Lin & Ying, 2014; Ruiz & Stützle, 2007). During the *destruction* phase, a partial candidate solutionπ_p is obtained by removing a fixed number (α) of elements from a current candidate solution π. Subsequently, during the *construction* phase, a greedy constructive heuristic is utilized to sequentially insert the removed elements into the partial solution π_p until a full solution is re-constructed. An acceptance criterion is then applied to determine whether the new solution replaces the incumbent solution. The process iterates through the *destruction* and *construction* phases, until certain termination conditions are met.

To further improve the performance of basic *IG* heuristic, local search heuristic is applied to the new solution generated during the construction phase. Because the *construction* phase of the basic *IG* heuristic has applied the insertion operation to generate new solution, the local search only uses exchange operation. We have designed and tested two versions of the local search heuristic. The results of computational study indicate that, under the same computational time, the *IG* heuristics performs better when either one of the two local search heuristics is used.

The following subsections discuss the solution representation, objective function calculation, and main steps of the proposed *IG* heuristic in further detail.

3.1. Solution representation and objective function value calculation

A TD-PARP solution is represented by a string of numbers comprising a permutation of n prize arcs, denoted by the set $\{1, 2, \ldots, n\}$. The jth number indicates the jth prize arc to be visited. Thus, the first element in a solution indicates the first arc to be visited. Other arcs are added to the tour, one by one, from left to right, to represent the visiting sequence, provided that the route duration constraint is not violated. If adding a prize arc to the tour

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