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Discrete Optimization

Fast heuristics for the Steiner tree problem with revenues, budget and hop constraints

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Abstract

This article describes and compares three heuristics for a variant of the Steiner tree problem with revenues, which includes budget and hop constraints. First, a greedy method which obtains good approximations in short computational times is proposed. This initial solution is then improved by means of a destroy-and-repair method or a tabu search algorithm. Computational results compare the three methods in terms of accuracy and speed.

Keywords: Prize collecting; Network design; Steiner tree problem; Budget; Hop constraints; Heuristics; Tabu search

1. Introduction

Network design problems arise in a large variety of real-life situations. In particular, spanning trees are used to model and solve planning problems frequently encountered in telecommunications (Voß, 2006) and electricity distribution (Carneiro et al., 1996; Avella et al., 2005).

The purpose of this article is to develop heuristics for the *Steiner Tree Problem with Revenues, Budget and Hop Constraints* (STPRBH). This problem is a generalization of several well-studied problems such as the *Minimum Spanning Tree Problem* (MSTP) and the *Steiner Tree Problem* (STP) described as follows. Let $G = (V, E)$ be a graph with vertex set $V = \{1, \ldots, n\}$, where vertex 1 is the *root* vertex, and edge set $E = \{(i,j) : i, j \in V, i < j\}$. In what follows, (i,j) must be interpreted as (j,i) if $i > j$. Each vertex has an associated revenue $r_i \geqslant 0$, and each edge has an associated cost $c_{ij} \geqslant 0$. Also, let T be a tree in G, and let $v(T)$ and $e(T)$ be the sets of vertices and edges belonging to T, respectively. The STPRBH is the problem of determining

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a tree T of maximal revenue $r(T) = \sum_{i \in v(T)} r_i$, rooted at vertex 1, and subject to two constraints: a budget constraint limiting the network cost $\sum_{(i,j) \in e(T)} c_{ij}$ to a maximum value b, and hop constraints limiting the number of edges h_i between $i \in v(T)$ and the root vertex to a maximum value h.

The STP is a well-studied problem and so is its version with revenues. The latter problem is useful in situations where one must decide whether or not to serve certain vertices. The idea is that one is not obliged to serve all vertices as in the MST, or specified vertices as in the STP. Instead, the number and location of the vertices to be served are part of the decision problem. For example, a cable television company planning to expand its network can decide whether or not to serve a certain area, based on the combination of the expected revenues that will come from the clients in that area and the network expansion cost. Steiner tree problems with revenues have been used to solve design problems in local access networks (Canuto et al., 2001; Cunha et al., 2003), and in heating networks (Ljubić et al., 2005). In network expansion problems, one is usually faced with budgetary constraints that come from the fact that a limited investment budget is available for a certain area or a certain period of time. Although it is quite easy to understand the practical aspect of these constraints, budget considerations are almost always ignored when dealing with STP with revenues (Costa et al., 2006b).

Concerning the hop constraints, their inclusion enables the consideration of reliability or transmission delays in the network. LeBlanc et al. (1999) have investigated the effect of hop constraints both on the reliability and on the maintenance of the signal quality in packet-switched telecommunication networks. Gouveia and Magnanti (2003) also use hop constraints to guarantee quality of service in telecommunications networks. Other uses of hop constraints have also been proposed in the literature. Balakrishnan and Altinkemer (1992) have imposed hop constraints to generate alternative communications networks, while Voß (1999) has mentioned the utility of these constraints to model time durability constraints when solving some classes of lot-sizing problems by means of spanning tree models.

In this article we propose heuristic methods for the STPRBH. A previous study (Costa et al., forthcoming) has shown the limits of exact algorithms for this problem. The heuristic methods proposed here are intended to obtain good approximations for large scale problems for which exact algorithms fail to converge. Several exact and heuristic methods already exist for the STP with profits (Costa et al., 2006b) and for spanning problems with hop constraints but, to our knowledge, no one has ever proposed approximate algorithms for the more general STPRBH. The closest problems solved by means of heuristic methods seem to be the MST and the STP with hop constraints. Lagrangian relaxation heuristics have been proposed for the MST with hop constraints (Gouveia, 1995, 1996, 1998; Gouveia and Requejo, 2001) and for the STP with hop constraints (Gouveia, 1998), while Voß (1999) has developed a greedy method and a tabu search algorithm for the hop constrained STP.

We first propose a fast greedy algorithm which is followed by one of the following two improvement phases: a simple local search that destroys part of the solution and rebuilds it in a greedy fashion, or a more flexible tabu search algorithm that explores the solution space by means of two simple neighborhoods. In the remainder of this article we describe these three algorithms in detail. In the next section, we provide a mathematical formulation for the STPRBH in order to help understand the ideas behind the heuristics. Then, the algorithms themselves are described. The greedy and the destroy-and-repair approaches are presented in Sections 3 and 4, respectively. Section 5 describes the tabu search algorithm while computational results are provided in Section 6. The paper ends with some conclusions in Section 7.

2. Mathematical formulation

We first recall the undirected Dantzig–Fulkerson–Johnson model for the STPRBH presented in (Costa et al., forthcoming). Constraints (4) and (5) of this model are useful to understand our heuristics. Let x_{ij} and y_i be binary variables associated with edges $(i,j) \in E$ and vertices $i \in V$, respectively. Variable y_i is equal to 1 if vertex i belongs to the solution ($y_1 = 1$), and to 0 otherwise. Similarly, variable x_{ij} is equal to 1 if edge (i,j) belongs to the solution, and to *0* otherwise. For $S \subseteq V$, define $E(S)$ as the set of edges with both end vertices in S. Let also $P = (i_1 = 1, \ldots, i_\ell)$ denote a path originating at the root vertex and containing ℓ vertices. Finally, define $\mathscr{P}_h$ as the set of paths P with $\ell = h + 2$, i.e., paths with $h + 1$ edges. The STPRBH can then be written as

$$\text{Maximize} \quad \sum_{i \in V} r_i y_i \tag{1}$$

$$\text{subject to} \quad \sum_{(i,j) \in E} x_{ij} = \sum_{i \in V} y_i - 1, \tag{2}$$

$$\sum_{(i,j) \in E(S)} x_{ij} \leqslant \sum_{i \in S \setminus \{k\}} y_i, \quad k \in S \subseteq V, \ |S| \geqslant 2, \tag{3}$$

$$\sum_{(i,j) \in E} c_{ij} x_{ij} \leqslant b, \tag{4}$$

$$\sum_{t=2}^{\ell} x_{i_{t-1}, i_t} \leqslant h, \quad P = (i_1 = 1, \ldots, i_\ell) \in \mathscr{P}_h, \tag{5}$$

$$x_{ij} \in \{0,1\}, \quad (i,j) \in E,$$

$$y_1 = 1, \tag{6}$$

$$y_i \in \{0,1\}, \quad i \in V \setminus \{1\}. \tag{7}$$

The goal is to maximize the collected revenues while respecting the budget and hop constraints, (4) and (5), respectively. Constraint (2) guarantees that in the solution the number of edges is equal to the number of vertices minus one, and constraints (3) are the connectivity constraints.

3. Greedy algorithm

The idea of our greedy algorithm is to iteratively construct a rooted tree while maintaining the feasibility of constraints (4) and (5). We start with a solution containing only the root vertex. At each step of the algorithm, one adds a path connecting a non-selected profitable vertex to the existing solution. The algorithm stops when it cannot find a profitable vertex that can be added to the solution without incurring a violation of either the budget or the hop constraints. Two basic steps are needed to implement this idea. First, one must be able to produce feasible paths connecting non-selected profitable vertices to the existing solution. Second, one must evaluate these paths and choose the best one (in a greedy sense). These two steps are now detailed.

3.1. Finding feasible paths

Adding at each step of the algorithm a path not creating cycles to the existing solution guarantees the satisfaction of constraints (2) and (3). In order to respect the budget constraint, the sum of the edge costs in the added path plus the costs of the edges already in the solution must not exceed the budget value. Therefore, one has interest in finding shortest paths connecting profitable vertices to the current tree. On the other hand, the number of the edges in a path must be limited, in order to respect the hop constraints. It is important to note that it does not suffice to guarantee that the added paths have less than h edges. Instead, one must also ensure that the number of edges in the complete path from the added profitable vertex to the root vertex (which might include edges that were already in the existing solution) is limited to h.

Based on these two considerations, it is easy to conclude that a building block for constructing feasible paths is the hop constrained shortest path problem, i.e., the problem of determining a shortest path between two vertices containing at most h edges. This problem can be solved efficiently by dynamic programming (Lawler, 1976). Let $L(i,j,\ell)$ represent the cost of a shortest path between an origin vertex i and a destination vertex j, containing at most ℓ edges. Then

$$L(i,i,0) = 0, \quad i \in V,$$

$$L(i,j,0) = \infty, \quad i,j \in V, \ j \neq i,$$

$$L(i,j,\ell) = \min\{L(i,j,\ell-1), \min_{k|(k,j) \in E} \{L(i,k,\ell-1) + c_{kj}\}, \quad i,j \in V, \ \ell \geqslant 1.$$

Note that, contrary to what happens in the shortest path problem, an optimal subpath between two vertices is dependent on the complete path to which it belongs. This happens due to the hop constraints, as shown in

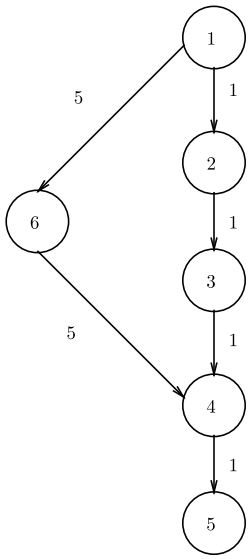

Fig. 1. Example of different optimal subpaths between two vertices depending on the complete path.

Fig. 1. Costs are shown next to the edges. The figure depicts optimal shortest paths from vertex 1 to the other vertices in the graph, with a hop limit of 3. Consider the optimal subpath from vertex 1 to vertex 4. This subpath includes vertices 2 and 3 if vertex 4 is the destination, but, in order to respect the hop limit, it includes only vertex 6 if vertex 5 is the destination. In implementation terms, this means that one must keep a precedence array for each vertex of the graph vertices while solving the problem.

With an algorithm for the shortest path problem with hop constraints, one can evaluate the cost of connecting the non-selected profitable vertices to the existing tree and develop a simple algorithm. Let T be the current solution. At the first iteration, $v(T) = \{1\}$ and the candidate destination vertices j are those with $L(1, j, h) \leqslant b$ and $r_j > 0$. Note that if a path violates the hop constraint, the hop constrained shortest path will return ∞, since we stop the dynamic programming algorithm after h steps. Therefore, paths violating the hop constraint will not be considered for insertion in the solution. When at least one path has been added, one must not only consider the new paths that originate at the root vertex, but also all paths that are originated at other vertices in $v(T)$. The algorithm considers for insertion all shortest paths such that

$$L(i, j, h - h_i) \leqslant b - \sum_{(i,j)\in e(T)} c_{ij}, \quad i \in v(T),\ j \notin v(T), r_j > 0.$$

Instead of running the hop constrained shortest path algorithm for all vertices in the current solution, we set the costs of the edges in $e(T)$ to *0* and run the algorithm a single time, with the root vertex as the origin. Because of the dynamic programming structure, a single run is able to compute the hop constrained shortest distances from the root to all the other vertices, saving computation time.

3.2. Evaluating the paths

At each step, a single new path is added to the solution. The criterion used to choose the path to be added is an important part of the algorithm. If one makes a choice based only on profits, there is a risk of adding very costly paths that will soon consume the whole budget. On the other hand, if one chooses to add shortest paths, some vertices with a high revenue but at a moderate distance from the current solution may be ignored. Based on preliminary tests, we found that the best strategy was to consider both the costs and the revenues when deciding on the path to be added. We tested several ratios r_j^α / c^β, where α and β are two non-negative numbers, r_j is the revenue of the profitable vertex to be added, and c is the sum of the cost of the edges in the path. We found that the best parameter setting was $\alpha = 3$ and $\beta = 1$, which was used in all subsequent tests.

Algorithm 1. Greedy algorithm for the STPRBH

```
1: T is initially the root node: v(T) = {1}.
2: p̄ = 1;
3: while p̄ ≠ 0 do
4:    p̄ = 0, c̄ = 0, j̄ = −1.
5:    for all vertices j ∉ v(T) do
6:       c = L(1, j, h);
7:       p = r_j^3 / c.
8:       if Σ_{(i,j)∈e(T)} c_ij + c > b then
9:          p = 0.
10:      end if
11:      if p ⩾ p̄ then
12:         j̄ = j;
13:         c̄ = c;
14:         p̄ = p.
15:      end if
16:   end for
17:   if p̄ ≠ 0 then
18:      P is the path from 1 to j̄: P = (i_1 = 1, ..., i_ℓ = j̄);
19:      c_{i_t, i_{t+1}} = 0, t = 1, ..., ℓ − 1;
20:      v(T) = v(T) ∪ v(P);
21:      destroy possible cycles.
22:   end if
23: end while
24: Return T.
```

Algorithm 1, described in the figure above, presents the complete greedy algorithm in details. A few comments on this algorithm are in order. First, note that when adding a path one can also add other profitable vertices in addition to the end vertex. It has proved to be slightly better not to consider these profits when deciding which path should be added. This way, the algorithm tends to add shorter paths first, thus reducing the risk of making wrong decisions due to the myopic character of the choices. Second, because of the hop constraints, one can sometimes introduce cycles when adding a path. Consider again Fig. 1 and the situation where $h = 3$, all vertices are profitable and, after the first iteration of the greedy algorithm $v(T) = \{1,2,3,4\}$. Assuming that the budget constraint is not violated, the algorithm will try to add vertex 5 to the solution, using the edges $(1,6)$ and $(6,4)$ in order to respect the hop constraint and therefore forming a cycle. When this situation happens, the algorithm destroys the cycle by inspecting vertices with two incoming edges (in this case, vertex 4) and eliminating the edge that was inserted first (in this case, edge $(3,4)$). This way, the cycle is eliminated and the hop constraints are respected for the entire graph.

4. Destroy-and-repair algorithm

The idea of destroying part of the solution and reconstructing it in a different way in order to obtain different and hopefully better solutions has already been used to solve other combinatorial problems. Ropke and Pisinger (2006) have employed such a technique to solve vehicle routing problems with time windows, and Pisinger and Ropke (2007) have applied it to a more general class of routing problems. Voß (1999) has successfully used a similar idea to solve the STP with hop constraints. For the STPRBH, we propose a very simple procedure that consists of sequentially blocking part of the current solution and rerunning the greedy algorithm.

A feasible solution to the STPRBH consists of a tree. Given an initial solution, we simply set the cost of some edges to infinity, one at a time, and we rerun the greedy algorithm with the modified costs. This is done for all edges of the current solution that are incident to a leaf vertex, as shown in Fig. 2, and the best obtained solution is retained. The procedure is repeated for the new solution until there is no gain obtained with the blocking of a single edge. Algorithm 2 schematically presents the procedure.

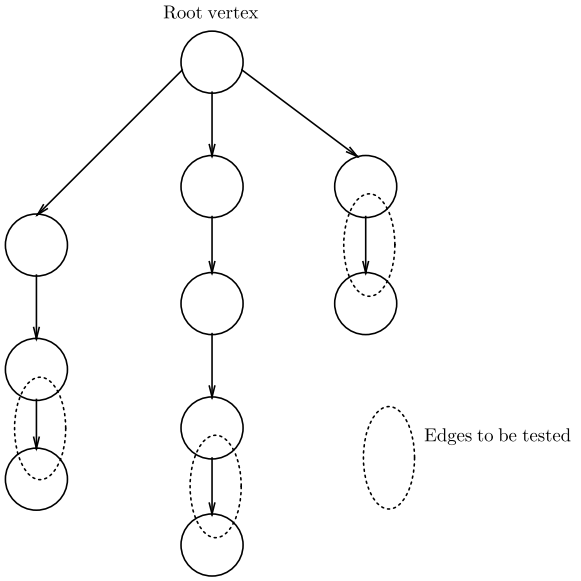

Fig. 2. Edges incident to leaf vertices.

Algorithm 2. Destroy-and-repair algorithm for the STPRBH

```
T = solution of Algorithm 1;
best solution T̄ = T.
y = true
while y = true do
    y = false
    for all the edges (i,j) incident to a leaf vertex do
        store original cost: c̄_ij = c_ij;
        c_ij = ∞;
        T= solution of Algorithm 1 (with modified costs).
        if r(T) > r(T̄) then
            y = true
            T̄ = T.
        end if
        Restore original cost: c_ij = c̄_ij.
    end for
end while
T = T̄;
return T
```

Other ways of preventing the greedy algorithm from repeatedly reaching the same solution can be used. For example, one could block all edges in the solution, one at a time. We tested this idea and, although it was much more time consuming, the results were not much better than the ones obtained with Algorithm 2. In a way this was expected, since the greedy algorithm has a tendency to reconstruct a similar solution if an intermediate edge has been blocked. By concentrating on the edges incident to profitable leaf vertices we increase the probability of really blocking that solution and obtaining something new.

We also tested other neighborhoods such as blocking a vertex of the solution (by setting the cost of all its incident edges to infinity). The results turned out to be worse than those obtained with the original algorithm. In this case, we think that the explanation comes from the fact that blocking a vertex is probably too restrictive and by doing so we may eliminate several good solutions. Finally, we have also tested the possibility of blocking more than one arc at the same time. Although minor improvements were obtained, the computational times were considerably larger and this option was also discarded.

5. Tabu search algorithm

A tabu search algorithm was also developed for the STPRBH. The main idea of tabu search is to define a neighborhood for a solution and let the algorithm explore the search space by moving to the best allowed neighbor solutions, while defining some forbidden or tabu moves in order to avoid cycling.

We define two basic moves for the STPRBH. The first is an *add* move. It consists of adding a path originating at a vertex of the current solution and ending at a profitable vertex. This is very similar to the basic step of the greedy algorithm presented in Section 3, since this move also makes use of the shortest path with hop constraints procedure and, therefore, maintains hop-feasibility during the whole search. In order to increase the flexibility of the algorithm, we let the *add* move violate the budget constraint. The idea is to design an algorithm capable of exploring infeasible parts of the search space in the hope of reaching feasible solutions that could not be reached otherwise. To encourage the identification of feasible solutions during the search, a penalty is associated with trees that violate the budget. The idea of letting the tabu search explore infeasible areas of the search space has been used successfully in other combinatorial problems (see, e.g., Gendreau et al., 1994).

The second move is *remove*, which consists of the deletion of a branch of the solution. It is the counterpart of the *add* move in the sense that the *add* move is driven by revenue collection, while the *remove* move is driven by budget-feasibility. In the following, the two moves are described in detail. A third move, which is called *destroy* is also described. We have used this move only occasionally to help the search algorithm escape from local optima.

With respect to several tabu search implementations developed for the solution of combinatorial optimization problems, our algorithm is relatively simple. This is a deliberate choice. In line with Cordeau et al. (2002), we believe it is preferable to design algorithms that are both accurate and simple. This makes them easy to reproduce and it favours their adoption by other researchers.

5.1. Add move

An *add* move is like a single step of the greedy algorithm described in Section 3: one adds the hop constrained shortest path connecting the best non-selected vertex to the current tree. This is done by setting the edge costs in the current solution to 0 and running the hop constrained shortest path procedure, which returns the hop constrained shortest paths originating at the root and ending at each vertex of the graph. Once a vertex has been added, it is declared tabu for a number of iterations. This way, the branch connecting the previous solution to the newly added vertex will not be deleted by the *remove* move until its tabu status has been lifted.

The tabu mechanism helps avoid cycling and forces the algorithm to explore new areas of the search space, differentiating the tabu search from the greedy algorithm presented earlier. Another strategy is used to increase the diversification of the solutions. At each iteration, one considers only a subset of randomly selected vertices: the algorithm arbitrarily chooses a subset of the possible vertices and adds the best one. Note that this is not done to save any computational time since the needed information was already available from the hop constrained shortest path procedure even for the discarded vertices, but as a diversification mechanism.

5.2. Remove move

The *remove* move consists of eliminating branches of the current solution. It was made necessary as a counterpart of the *add* move in order to help the algorithm identify budget-feasible solutions. We carefully select the branches to be eliminated in order to introduce only local perturbations in the current solution. This is done by connecting a vertex with degree larger or equal to three to a leaf of the current tree. For a current solution T, we call $B(T)$ the set of vertices with degree larger or equal to three. These vertices are called *breaking points*, since it is at these vertices that the solution is cut. Fig. 3 depicts an example of a tree solution. The breaking points are highlighted while the possible paths to be cut are shown in dotted lines.

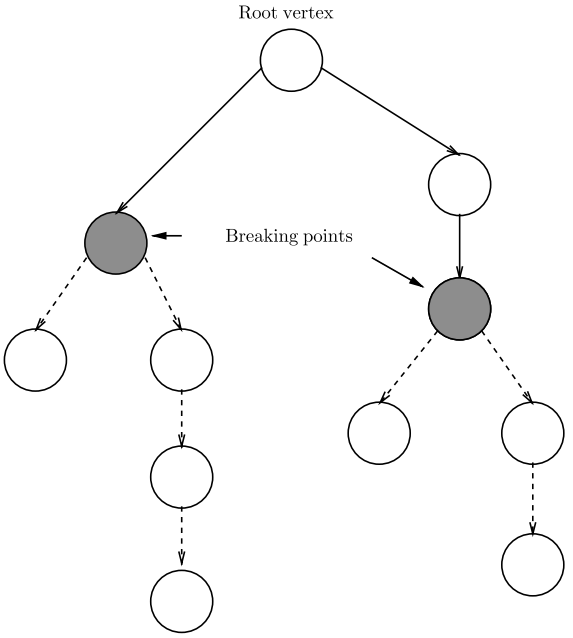

Fig. 3. Breaking points and possible paths to be removed.

5.3. Destroy move

A *destroy* move that erases a whole subtree of the current solution has also been developed. This move acts by randomly selecting a vertex in the current solution and deleting the whole subtree rooted at that vertex. This move was only used after the algorithm spent a certain number of iterations without improving the best known solution value.

The three moves just described have been incorporated within the tabu search algorithm. The *add* and *remove* moves are evaluated together. First, the gain of all *add* moves is computed. The gain of one *add* move connecting the profitable vertex i to the solution is given by the value of the revenue of the added vertex, minus the difference between the penalties after and before the move:

$$\gamma_i^+ = r_i - \pi(T') + \pi(T''),$$

where $\pi(T)$ is the penalty associated with a solution T, and T' and T'' are the solutions before and after the move, respectively. For a given solution T with total network cost $\sum_{(i,j)\in e(T)} c_{ij}$, the penalty is given by

$$\pi(T) = \begin{cases} 0 & \text{if } \sum_{(i,j)\in e(T)} c_{ij} \leqslant b, \\ \phi \times \left[\sum_{(i,j)\in e(T)} c_{ij} - b \right] & \text{if } \sum_{(i,j)\in e(T)} c_{ij} > b, \end{cases}$$

where ϕ is a penalty parameter updated dynamically during the search. The parameter ϕ is initialized at 1, but the algorithm is robust with respect to this parameter.

In a complementary manner, the *remove* move for a node $i \in B(T)$ yields a gain equal to:

$$\gamma_i^- = -r_i - \pi(T') + \pi(T'').$$

At each iteration, the move with the best gain is performed and the penalty parameter ϕ is updated. If the new solution is budget feasible, ϕ is halved, thus encouraging the algorithm to look for budget-infeasible solutions. Similarly, if the new solution is budget-infeasible, ϕ is doubled.

Algorithm 3 presents the tabu search algorithm in detail. It stops after a preset number of iterations.

Algorithm 3. Tabu search algorithm for the STPRBH

```
1: T = solution of Algorithm 1;
2: T̄ = T;
3: φ = 1.
4: while stopping criterion not reached do
5:    Randomly select a subset R(T) of the profitable vertices not in the tree and compute gain,
      γ_i^+ = r_i − π(T′) + π(T″), i ∈ R(T);
6:    compute gain for all remove moves, γ_i^− = −r_i − π(T′) + π(T″), i ∈ B(T);
7:    perform move with best gain (γ_i^− or γ_i^+) and update T;
8:    make move tabu for 5 iterations.
9:    if solution is budget-feasible then
10:      φ = φ/2.
11:      if r(T) > r(T̄) then
12:         T̄ = T.
13:      end if
14:   else
15:      φ = 2φ.
16:   end if
17:   if no improvement in more than 100 iterations then
18:      apply destroy move.
19:   end if
20: end while
```

6. Computational experiments

We have tested the algorithms just described on several instances obtained from the OR-Library (Beasley, 1990). The STP instances contain two set of vertices: *mandatory* vertices which must be present in the solution, and *Steiner* vertices which can be used if their inclusion in the solution reduces the total cost. We have adapted these instances for the STPRBH by using the mandatory vertices as profitable vertices with revenue given by a discrete uniform distribution on 1 and 100. The Steiner vertices were attributed a zero revenue. Different values for the budget and for the hop limit were attributed to each instance, thus creating several scenarios.

Table 1 summarizes the results obtained for a mid-sized group of 144 instances, ranging from 50 to 500 vertices and from 63 to 625 edges. Note that for these instances, the exact methods presented by Costa et al. (forthcoming) were able to converge within a time limit of 2 hours, allowing them to be used as benchmarks to evaluate the approximate algorithms. In the table, for each method (greedy algorithm, destroy-and-repair and tabu search), we report the mean and maximum gap, as well as the mean and maximum computation times. There are two entries for the Tabu search algorithm, each corresponding to a maximum allowed number of iterations (2000 or 10,000). Complete results can be found in Costa et al. (2006a).

Even the simplest of the three algorithms can solve a large number of instances to optimality. Indeed, the greedy algorithm finds an optimal solution for 73 out of the 144 instances. Note that we did not consider instances with a budget equal to the total network cost since these instances are easy and the greedy algorithm always finds an optimal solution. It is clear, however, that for some instances the greedy algorithm can be trapped in a poor quality local optimum. In the worst of the cases, the algorithm generated a solution with

Table 1
Summary of results for the mid-sized instances

Method	Gap (%)	Max Gap (%)	Seconds	Max seconds
Greedy	2.50	31.97	<0.01	0.02
Destroy-and-repair	1.13	10.10	0.09	1.44
Tabu (2000)	0.52 ± 0.08	12.99 ± 7.55	0.38	0.90
Tabu (10,000)	0.24 ± 0.05	8.46 ± 8.01	1.80	4.21

Table 2
Summary of results for the larger instances

Method	Improvement (%)	Max improvement (%)	Seconds	Max seconds
Greedy	–	–	1.94	31.78
Destroy-and-repair	1.31	14.36	312.50	6493.60
Tabu (2000)	1.41 ± 0.06	20.80 ± 2.60	44.98	287.64
Tabu (10,000)	2.00 ± 0.04	23.05 ± 2.14	237.53	1668.60

an optimality gap almost equal to 32%. Finally, concerning the computational time, since the algorithm is based on quick shortest paths calculations, a maximum of 0.02 seconds was required to solve any instance.

Starting from the solution of the greedy algorithm, both the destroy-and-repair and the tabu search were able to reduce the optimality gaps. The first method reduced the mean gap from 2.50% to 1.13% and the maximum gap from 32% to 10.10%. The tabu search was able to further reduce these gaps. The mean gap (averaged over ten runs) was reduced to 0.52% when 2000 iterations were allowed, and to 0.24% when 10,000 iterations were allowed. The maximum gaps for these two cases were 12.99% and 8.46%.

To better evaluate the efficiency of the improvement routines, we consider a second group of larger instances with up to 500 vertices and 12,500 edges. For these instances, the exact algorithms described in Costa et al. (forthcoming) generally did not obtain solutions within the allowed time limit of 2 hours, often failing to even solve the linear relaxation at the root node. For this reason, we compare the results obtained by the destroy-and-repair and the tabu search methods to the results obtained by the greedy algorithm. Table 2 presents a summary of the results. We can see that even for large instances, the greedy algorithm is very fast, taking on average 1.94 seconds, with a maximum of 31.78 seconds. Still concerning the times, it is interesting to see how the destroy-and-repair can easily become very computationally inefficient, taking almost 2 hours to solve some of the instances. The tabu search, even when run for 10,000 iterations, is on average 30% faster than the destroy-and-repair algorithm and presents much more stable computing times. The complete set of results is presented in Costa et al. (2006a).

Concerning the improvements, the destroy-and-repair algorithm yields mean and maximum improvements of 1.31% and 14.36%, respectively. The tabu search can increase these percentages to 1.41% and 20.80% when run for 2000 iterations, and obtains considerably better solutions when 10,000 iterations are allowed. It then yields 2.00% average improvement in comparison to the greedy algorithm, and a maximum improvement of more than 23%.

7. Conclusions

We have proposed three heuristics for a modified version of the Steiner Tree Problem with revenues including budget and hop constraints. A former study (Costa et al., forthcoming) has shown that exact algorithms based on existing formulations cannot be applied to large instances of this problem. The heuristics we have proposed are based on simple construction and tabu search mechanisms. The greedy algorithm is extremely fast but may be trapped in a local optimum due to its myopic nature. The destroy-and-repair method is a simple modification of the greedy algorithm which considerably improves its solutions, albeit at the cost of a large increase in computation time. Finally, the tabu search is capable of consistently identifying optimal solutions while maintaining the computational times at a reasonable level.

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