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# Greedy Like Algorithms for the Traveling Salesman and Multidimensional Assignment Problems

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## 1. Introduction

Majority of chapters of this book show usefulness of greedy like algorithms for solving various combinatorial optimization problems. The aim of this chapter is to warn the reader that not always a greedy like approach is a good option and, in certain cases, it is a very bad option being sometimes among the worst possible options. Our message is not a discouragement from using greedy like algorithms altogether; we think that for every combinatorial optimization problem of importance, researchers and practitioners should simply investigate the appropriateness of greedy like algorithms and the existence of better alternatives to them (considering both quality of solution and running time). In many cases, especially when the running time must be very short, the conclusion may still be that the most practical of known approaches is a greedy like algorithm.

The Traveling Salesman and Multidimensional Assignment Problems are optimization problems for which greedy like approaches are usually not very successful. We demonstrate this by providing both theoretical and experimental results on greedy like algorithms as well as on some other algorithms that produce (in theory and/or in experiments) much better results without spending significantly more time.

There are some general theoretical results that indicate that there are, in fact, many combinatorial optimization problems for which greedy like algorithms are not the best option even among fast construction heuristics, see, e.g., [3, 5, 17]. We will not consider these general results in order to avoid most mathematical details that are not necessary for understanding the results of this chapter. For this reason we will not give proofs here apart from two simple proofs: that of Theorem 8 which shows that some instances on which the greedy algorithm fails are not exotic in a sense and that of Theorem 11 since Theorem 11 is a new result.

It is not a trivial question whether a certain algorithm is greedy like or not. In the next section we define an independence system and give the classic definition of the greedy algorithm for such a system. We extend this definition to so-called greedy type algorithms that include such well-known algorithms as the Prim's algorithm for the minimum spanning tree problem and the nearest neighbor algorithm for the traveling salesman problem. We use the term 'greedy like' in an informal way and we include in this class simple and fast construction heuristics that seem to us to be of greedy nature.

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Unfortunately, no formal definition exists for the wide family of greedy like algorithms and one can understand the difficulty to formally classify such algorithms by, for example, considering local search algorithms which find the best solution in each neighborhood they search. Intuitively, it is clear that such local search algorithms are not greedy yet their every search is greedy in a sense.

In the next section, we give most of terminology and notation used in this chapter. Several results on theoretical performance of greedy like algorithms for the Traveling Salesman and Multidimensional Assignment Problems are discussed in Sections 3 and 4, respectively. Experimental results on greedy like algorithms for the Traveling Salesman and Multidimensional Assignment Problems are given and analyzed in Sections 5 and 6, respectively.

## 2. Terminology and notation

The *Asymmetric Traveling Salesman Problem (ATSP)* is the problem of computing a minimum weight tour (Hamilton directed cycle) passing through every vertex in a weighted complete digraph  $K_n^*$  on  $n$  vertices. The *Symmetric TSP (STSP)* is the same problem, but on a weighted complete undirected graph  $K_n$ . When a certain fact holds for both ATSP and STSP, we will simply speak of *TSP*. We often assume that the vertices of  $K_n^*$  and  $K_n$  are  $1, 2, \dots, n$  and often refer to the weight  $w(ij)$  of an edge  $ij$  of  $K_n^*$  (or  $K_n$ ) as the *distance* from  $i$  to  $j$ . TSP has a large number of applications, see, e.g., the two recent books [1, 13] on TSP.

The *Multidimensional Assignment Problem (MAP)* (abbreviated *s-AP* in the case of  $s$  dimensions) is a well-known optimization problem with a host of applications (see, e.g., [2, 6, 7] for 'classic' applications and [4, 25] for recent applications in solving systems of polynomial equations and centralized multisensor multitarget tracking). In fact, several applications described in [4, 6, 25] naturally require the use of *s-AP* for values of  $s$  larger than 3.

For a fixed  $s \geq 2$ , the *s-AP* is stated as follows. Let  $X_1 = X_2 = \dots = X_s = \{1, 2, \dots, n\}$ . We will consider only vectors that belong to the Cartesian product  $X = X_1 \times X_2 \times \dots \times X_s$ . Each vector  $e \in X$  is assigned a non-negative integral weight  $w(e)$ . For a vector  $e \in X$ , the component  $e_j$  denotes its  $j$ th coordinate, i.e.,  $e_j \in X_j$ . A collection  $A$  of  $t \leq n$  vectors  $e^1, e^2, \dots, e^t$  is a (*feasible*) *partial assignment* if  $e_j^i \neq e_j^k$  holds for each  $i \neq k$  and  $j \in \{1, 2, \dots, s\}$ . The *weight* of a partial assignment  $A$  is  $w(A) = \sum_{i=1}^t w(e_i)$ . An *assignment* (or *full assignment*) is a partial assignment with  $n$  vectors. The objective of *s-AP* is to find an assignment of minimum weight.

Let  $\mathcal{P}$  be a combinatorial optimization problem and let  $\mathcal{H}$  be a heuristic for  $\mathcal{P}$ . The *domination number*  $\text{domn}(\mathcal{H}, \mathcal{I})$  of  $\mathcal{H}$  for an instance  $\mathcal{I}$  of  $\mathcal{P}$  is the number of solutions of  $\mathcal{I}$  that are not better than the solution  $s$  produced by  $\mathcal{H}$  including  $s$  itself. For example, consider an instance  $\mathcal{I}$  of the STSP on 5 vertices. Suppose that the weights of tours in  $\mathcal{I}$  are 2, 5, 5, 6, 6, 9, 9, 11, 11, 12, 12, 15 (every instance of STSP on 5 vertices has 12 tours) and suppose that the greedy algorithm computes the tour  $\mathcal{T}$  of weight 6. Then  $\text{domn}(\text{greedy}, \mathcal{I}) = 9$ . In general, if  $\text{domn}(\mathcal{H}, \mathcal{I})$  equals the number of solutions in  $\mathcal{I}$ , then  $\mathcal{H}$  finds an optimal solution for  $\mathcal{I}$ . If  $\text{domn}(\mathcal{H}, \mathcal{I}) = 1$ , then the solution found by  $\mathcal{H}$  for  $\mathcal{I}$  is the unique worst possible one. The *domination number*  $\text{domn}(\mathcal{H}, n)$  of  $\mathcal{H}$  is the minimum of  $\text{domn}(\mathcal{H}, \mathcal{I})$  over all instances  $\mathcal{I}$  of size  $n$ .

An *independence system* is a pair consisting of a finite set  $E$  and a family  $\mathcal{F}$  of subsets (called *independent sets*) of  $E$  such that (I1) and (I2) are satisfied.

(I1) the empty set is in  $\mathcal{F}$ ;

(I2) If  $X \in \mathcal{F}$  and  $Y$  is a subset of  $X$ , then  $Y \in \mathcal{F}$ .

All maximal sets of  $\mathcal{F}$  are called *bases* (or, *feasible solutions*).

Many combinatorial optimization problems can be formulated as follows. We are given an independence system  $(E, \mathcal{F})$ , a set  $W \subseteq \mathbb{Z}_+$  and a weight function  $w$  that assigns a weight  $w(e) \in W$  to every element of  $E$  ( $\mathbb{Z}_+$  is the set of non-negative integers). The weight  $w(S)$  of  $S \in \mathcal{F}$  is defined as the sum of the weights of the elements of  $S$ . It is required to find a base  $B \in \mathcal{F}$  of minimum weight. We will consider only such problems and call them the  $(E, \mathcal{F}, W)$ -*optimization problems*.

ATSP is an  $(E, \mathcal{F}, \mathbb{Z}_+)$ -optimization problem, where  $E$  is the set of arcs of the complete digraph  $K_n^*$  and  $\mathcal{F} = \{B \subseteq H : H \in \mathcal{H}\}$ , where  $\mathcal{H}$  is the set of Hamilton directed cycles of  $K_n^*$ . MAP is also an  $(E, \mathcal{F}, \mathbb{Z}_+)$ -optimization problem, where  $E$  is the set of all vectors and  $\mathcal{F}$  is the set of all partial assignments.

If  $S \in \mathcal{F}$ , then let  $I(S) = \{x : S \cup \{x\} \in \mathcal{F}\} \setminus S$ . This means that  $I(S)$  consists of those elements from  $E \setminus S$ , which can be added to  $S$ , in order to have an independent set of size  $|S| + 1$ . Note that by (I2)  $I(S) \neq \emptyset$  for every independent set  $S$  which is not a base.

The *Greedy Algorithm* (Greedy) tries to construct a minimum weight base as follows: it starts from an empty set  $X$ , and at every step it takes the current set  $X$  and adds to it a minimum weight element  $e \in I(X)$ , the algorithm stops when a base is built. We assume that the greedy algorithm may choose any element among equally weighted elements in  $I(X)$ . Thus, when we say that the greedy algorithm *may construct* a base  $B$ , we mean that  $B$  is built provided the appropriate choices between elements of the same weight are made.

Greedy type algorithms were introduced in [14]. They include the nearest neighbor algorithm for TSP and are defined as follows. A *greedy type* algorithm  $\mathcal{H}$  is similar to the greedy algorithm: start with the partial solution  $X = \emptyset$ ; and then repeatedly add to  $X$  an element of minimum weight in  $I_{\mathcal{H}}(X)$  (ties are broken arbitrarily) until  $X$  is a base of  $\mathcal{F}$ , where  $I_{\mathcal{H}}(X)$  is a subset of  $I(X)$  that does not depend on the cost function  $c$ , but only on the independence system  $(E, \mathcal{F})$  and the set  $X$ . Moreover,  $I_{\mathcal{H}}(X)$  is non-empty if  $I(X) \neq \emptyset$ , a condition that guarantees that  $\mathcal{H}$  always outputs a base.

### 3. Theoretical performance of greedy like algorithms for TSP

The main practical message of this and the next section is that one should be careful while using the classical greedy algorithm and its variations in combinatorial optimization: there are many instances of combinatorial optimization problems for which such algorithms will produce the unique worst possible solution. Moreover, this is true for several well-known optimization problems and the corresponding instances are not exotic, in a sense. This means that not always the paradigm of greedy optimization provides any meaningful optimization at all.

The first results of the kind mentioned in the previous paragraph were obtained in [19]:

**Theorem 1.** *For each  $n \geq 2$  there is an instance of ATSP for which the Greedy Algorithm finds the unique worst possible tour.*

Gutin, Yeo and Zverovitch [19] proved Theorem 1 also for the *Nearest Neighbor* (NN) algorithm: start from an arbitrary vertex  $i_1$  and go to a vertex  $i_2 \neq i_1$  with shortest distance

from  $i_1$ ; when in a vertex  $i_k$ ,  $k < n$ , go to a vertex  $i_{k+1}$  with shortest distance from  $i_k$  among vertices not in the set  $\{i_1, i_2, \dots, i_{k-1}\}$ . The proof for NN is correct for both ATSP and STSP. The proof of Theorem 1 itself (for Greedy) cannot be extended to STSP, but Theorem 1 holds also for STSP [18].

The Greedy and NN algorithms are special cases of greedy type algorithms and Bendall and Margot [5] proved the following result that generalizes all the results above.

**Theorem 2.** *Let  $\mathcal{A}$  be a TSP greedy type algorithm. For each  $n \geq 3$  there is an instance of TSP for which  $\mathcal{A}$  finds the unique worst possible tour.*

At this stage the reader may ask the following natural question: 'Perhaps, it is true that every TSP heuristic has the domination number equal 1?' The answer is negative. In fact, there are many TSP heuristics (see, e.g., [15, 23]) which, for every instance  $\mathcal{T}$  of TSP with  $n$  vertices ( $n \geq 3$ ), produce a tour that is no longer than the average length of a tour in  $\mathcal{T}$ . Among these heuristics there are several fast construction heuristics. Thus, we can apply the following theorem to many TSP heuristics (we formulate this theorem for ATSP, but an almost identical result by Rublineckii [26] is known for STSP, see [13]):

**Theorem 3.** *Let  $\mathcal{H}$  be an ATSP heuristics that, for every instance  $\mathcal{T}$  of ATSP on  $n \geq 2$  vertices, produces a tour that is no longer than the average length of a tour in  $\mathcal{T}$ . Then the domination number of  $\mathcal{H}$  is at least  $(n - 2)!$  for each  $n \neq 6$ .*

This theorem was first proved by Sarvanov [27] for odd values of  $n$  and by Gutin and Yeo [15] for even values of  $n$ .

Sometimes, we are interested in TSP with only restricted range of weights. The following two results for this variation of TSP were obtained by Bang-Jensen, Gutin and Yeo [3].

**Theorem 4.** *Consider STSP as an  $(E, \mathcal{H}, W)$ -optimization problem.*

- If  $n \geq 4$  and  $|W| \leq \lfloor \frac{n-1}{2} \rfloor$ , then the greedy algorithm never produces the unique worst possible base (i.e., tour).*
- If  $n \geq 3$ ,  $r \geq n - 1$  and  $W = \{1, 2, \dots, r\}$ , then there exists a weight function  $w : E \rightarrow \{1, 2, \dots, r\}$  such that the greedy algorithm may produce the unique worst possible base (i.e., tour).*

**Theorem 5.** *Consider ATSP as an  $(E, \mathcal{H}, W)$ -optimization problems. Let  $n \geq 3$ .*

- If  $|W| \leq \lfloor \frac{n-1}{2} \rfloor$ , then the greedy algorithm never produces the unique worst possible base (i.e., tour).*
- For every  $r \geq \lceil \frac{n+1}{2} \rceil$  there exists a weight function  $w : E(K_n^*) \rightarrow \{1, 2, \dots, r\}$  such that the greedy algorithm may produce the unique worst possible base (i.e., tour).*

Notice that the above-mentioned theorems can be proved as corollaries of general results that hold for many  $(E, \mathcal{H}, W)$ -optimization problems, see, e.g., [3, 5, 16].

Another ATSP greedy like heuristic, max-regret-fc (fc abbreviates First Coordinate), was first introduced by Ghosh et al. [8]. Extensive computational experiments in [8] demonstrated a clear superiority of max-regret-fc over the greedy algorithm and several other construction heuristics from [9]. Therefore, the result of Theorem 6 obtained by Gutin, Goldengorin and Huang [11] was somewhat unexpected.

Let  $Q$  be a collection of disjoint directed paths in  $K_n^*$  and let  $V = V(K_n^*) = \{1, 2, \dots, n\}$ . An arc  $a = ij$  is a *feasible addition* to  $Q$  if  $Q \cup \{a\}$  is either a collection of disjoint paths or a tour in  $K_n^*$ . Consider the following two ATSP heuristics: max-regret-fc and max-regret.

The heuristic *max-regret-fc* proceeds as follows. Set  $W = T = 0$ . While  $W \neq V$  do the following: For each  $i \in V \setminus W$ , compute two lightest arcs  $ij$  and  $ik$  that are feasible additions to  $T$ , and

compute the difference  $\Delta_i = |w(ij) - w(ik)|$ . For  $i \in V \setminus W$  with maximum  $\Delta_i$  choose the lightest arc  $ij$ , which is a feasible addition to  $T$  and add  $ij$  to  $M$  and  $i$  to  $W$ .

The heuristic *max-regret* proceeds as follows. Set  $W^+ = W^- = T = 0$ . While  $W^+ \neq V$  do the following: For each  $i \in V \setminus W^+$ , compute two lightest arcs  $ij$  and  $ik$  that are feasible additions to  $T$ , and compute the difference  $\Delta_i^+ = |w(ij) - w(ik)|$ ; for each  $i \in V \setminus W^-$ , compute two lightest arcs  $ji$  and  $ki$  that are feasible additions to  $T$ , and compute the difference  $\Delta_i^- = |w(ji) - w(ki)|$ . Compute  $i' \in V \setminus W^+$  with maximum  $\Delta_{i'}^+$  and  $i'' \in V \setminus W^-$  with maximum  $\Delta_{i''}^-$ . If  $\Delta_{i'}^+ \geq \Delta_{i''}^-$ , choose the lightest arc  $i'j'$ , which is a feasible addition to  $T$  and add  $i'j'$  to  $M$ ,  $i'$  to  $W^+$  and  $j'$  to  $W^-$ . Otherwise, choose the lightest arc  $j''i''$ , which is a feasible addition to  $T$  and add  $j''i''$  to  $M$ ,  $i''$  to  $W^-$  and  $j''$  to  $W^+$ .

Notice that in *max-regret-fc*, if  $|V \setminus W| = 1$  we set  $\Delta_i = 0$ . A similar remark applies to *max-regret*.

**Theorem 6.** *The domination number of both max-regret-fc and max-regret equals 1 for each  $n \geq 2$ .*

#### 4. Theoretical performance of greedy like algorithms for MAP

In this section, we will first prove that the greedy algorithm for s-AP is of domination number 1. The proof shows that the greedy algorithm fails on instances that cannot be called 'exotic' in the sense that they do not have very large weights. For our proof we need the following definitions and lemma.

A vector  $h$  is *backward* if  $\min\{h_i : 2 \leq i \leq s\} < h_1$ ; a vector  $h$  is *horizontal* if  $h_1 = h_2 = \dots = h_s$ . A vector is *forward* if it is not horizontal or backward.

**Lemma 7.** *Let  $F$  be an assignment of s-AP ( $s \geq 2$ ). Either all vectors of  $F$  are horizontal or  $F$  contains a backward vector.*

**Proof:** Let  $F = \{f^1, f^2, \dots, f^n\}$ , where  $f_1^i = i$  for each  $1 \leq i \leq n$ . Assume that not every vector of  $F$  is horizontal. We show that  $F$  has a backward vector. Suppose it is not true. Then  $F$  has a forward vector  $f^i$ . Thus, there is a subscript  $j$  such that  $f_j^i > i$ . By the pigeonhole principle, there exists a superscript  $k > i$  such that  $f_j^k \leq i$ , i.e.,  $f^k$  is backward; a contradiction.  $\square$

**Theorem 8.** *For each  $s \geq 2, n \geq 2$ , there exists an instance of s-AP for which Greedy will find the unique worst possible assignment.*

**Proof:** Consider some  $M > n$  and let  $E = \{e^1, e^2, \dots, e^n\}$ , where  $e^i = (i, i, \dots, i)$  for every  $1 \leq i \leq n$ . We define the required instance  $\mathcal{I}$  as follows:  $w(e^i) = iM$  for each  $1 \leq i \leq n$  and, for each  $f \notin E$ ,  $w(f) = \min\{f^i : 1 \leq i \leq s\} \cdot M + 1$ .

Observe that Greedy will construct  $E$ . Let  $F = \{f^1, f^2, \dots, f^n\}$  be any other assignment, where  $f_1^i = i$  for each  $1 \leq i \leq n$ . By Lemma 7,  $F$  has a backward vector  $f^k$ . Notice that

$$w(f^k) \leq (k - 1)M + 1 \tag{1}$$

By the definition of the weights and (1),

$$\begin{aligned} w(F) &= \sum_{i=1}^n w(f^i) = \sum_{i \neq k} w(f^i) + w(f^k) \\ &\leq \sum_{i \neq k} (iM + 1) + (k - 1)M + 1 \end{aligned}$$

$$\begin{aligned}
&= \sum_{i=1}^n iM + n - M \\
&< \sum_{i=1}^n iM = w(E).
\end{aligned}$$

□

One can consider various greedy type algorithms for  $s$ -AP. One natural algorithm of this kind proceeds as follows: At the  $i$ th iteration,  $i = 1, 2, \dots, n$  choose a vector  $e^i$  of minimum weight such that  $e_1^i = i$  and  $\{e^1, e^2, \dots, e^i\}$  is a partial assignment. We call this algorithm the *First Coordinate Fixing* (FCF) heuristic. A simple modification of the proof of the first half of Theorem 10 in [5] shows the following:

**Theorem 9.** *For every  $n \geq 1$ ,  $s \geq 2$ , there is an instance of  $s$ -AP and for every greedy type algorithm  $\mathcal{H}$  for  $s$ -AP, there is an instance  $I$  of  $s$ -AP for which  $\mathcal{H}$  finds the unique worst possible assignment.*

In Section 3, we considered the max-regret-fc and max-regret heuristics. In fact, max-regret was first introduced for 3-AP by Balas and Saltzman [2]. The  $s$ -AP heuristic *max-regret* proceeds as follows. We start from the empty partial assignment  $A$  and, at every iteration, we consider a partial assignment  $A$ . Set  $V_d = \{1, 2, \dots, n\}$  for each  $1 \leq d \leq s$ . For each dimension  $d$  and each value  $v \in V_d$  consider every vector  $e \in X'$  such that  $e_d = v$ , where  $X' \subset X$  is a set of feasible additional vectors, i.e.,  $A \cup \{e\}$  is a feasible partial assignment if  $e \in X'$ . If  $X' \neq \emptyset$ , find two vectors  $e_{\min}^1$  and  $e_{\min}^2$  in the considered subset  $Y_{d,v} = \{e \in X' : e_d = v\}$  such that  $e_{\min}^1 = \operatorname{argmin}_{e \in Y_{d,v}} w(e)$ , and  $e_{\min}^2 = \operatorname{argmin}_{e \in Y_{d,v} \setminus \{e_{\min}^1\}} w(e)$ . (If  $|Y_{d,v}| = 1$ , set  $e_{\min}^2 = e_{\min}^1$ .) Select the pair  $(d, v)$  that corresponds to the maximum difference  $w(e_{\min}^2) - w(e_{\min}^1)$  and add the vector  $e_{\min}^1$  for the selected  $(d, v)$  to the solution  $A$ . In computational experiments, Balas and Saltzman [2] compared the greedy algorithm with max-regret and concluded that max-regret is superior to the greedy algorithm with respect to the quality of solutions. However, after conducting wider computational experiments, Robertson [25] came to a different conclusion: the greedy algorithm and max-regret are of similar quality for 3-AP. Gutin, Goldengorin and Huang [11] share the conclusion of Robertson: both greedy algorithm and max-regret are of domination number 1 for  $s$ -AP for each  $s \geq 3$ . Moreover, there exists a common family of  $s$ -AP instances for which both heuristics find the unique worst assignment [11] (for each  $s \geq 3$ ).

Similarly to TSP, we may obtain MAP heuristics of factorial domination number if we consider not-worth-than-average heuristics. This follows from the next theorem:

**Theorem 10.** [11] *Let  $\mathcal{H}$  be a heuristic that for each instance of  $s$ -AP constructs an assignment of weight at most the average weight of an assignment. Then the domination number of  $\mathcal{H}$  is at least  $((n-1)!)^{s-1}$ .*

Using Theorem 10, it is proved in [11] that the following heuristic is of domination number at least  $((n-1)!)^{s-1}$ . The *Recursive Opt Matching* (ROM) heuristic proceeds as follows. Initialize the solution by trivial vectors:  $e^i = (i, i, \dots, i)$ ,  $i = 1, 2, \dots, n$ . On each  $j$ th iteration of the heuristic,  $j = 1, 2, \dots, s-1$ , calculate an  $n \times n$  matrix  $M_{i,v} = \sum_{e \in Y(j,i,v)} w(e)$ , where  $Y(j, i, v)$  is a set of all vectors  $e \in X$  such that the first  $j$  coordinates of the vector  $e$  are equal to the first  $j$  coordinates of the vector  $e^i$  and the  $(j+1)$ th coordinate of  $e$  is  $v$ :  $Y(j, i, v) = \{e \in X : e^k = e_k^i, 1 \leq k \leq j, \text{ and } e_{j+1} = v\}$ . Let permutation  $\pi$  be a solution of the 2-AP for the matrix  $M$ . We set  $e_{j+1}^i = \pi(i)$  for each  $1 \leq i \leq n$ .

The *Multi-Dimensionwise Variation* (MDV) heuristic is introduced in [12] as a local search heuristic for MAP. MDV starts from the trivial solution  $e^i = (i, i, \dots, i), i = 1, 2, \dots, n$ . On each step it selects a nonempty set of distinct dimensions,  $F \subsetneq \{1, 2, \dots, s\}$ . The corresponding dimensions are fixed, while the others are varied, and an  $n \times n$  matrix  $M_{ij} = w(v^{ij})$  is produced, where

$$v_d^{i,j} = \begin{cases} e_d^i & \text{if } d \in F \\ e_d^j & \text{if } d \notin F \end{cases} \quad \text{for } d = 1, 2, \dots, s.$$

Let permutation  $\rho$  be a solution of the corresponding 2-AP. If  $\rho$  is not an identity permutation, the heuristic changes the  $s$ -AP assignment in the following way:

$$e_d^i = \begin{cases} e_d^i & \text{if } d \in F \\ e_d^{\rho(i)} & \text{if } d \notin F \end{cases} \quad \text{for } i = 1, 2, \dots, n \text{ and } d = 1, 2, \dots, s.$$

There are  $2^s - 2$  distinct sets of the fixed dimensions  $F$ , but a half of them may be omitted since there is no difference whether to fix the selected dimensions and to vary the others, or to vary the selected dimensions and to fix the others. So, every iteration of the heuristic tries  $2^{s-1} - 1$  distinct sets  $F$ . If no improvement was obtained during an iteration, the algorithm terminates. We have the following:

**Theorem 11.** *The domination number of MDV equals  $(2^{s-1} - 1)(n! - 1) + 1$ .*

**Proof:** Let a vector  $e^i = (i, i, \dots, i) \in X$  for every  $i = 1, 2, \dots, n$  and let vectors  $e^{(i,j,F)} \in X, 1 \leq i \neq j \leq n$ , be defined as  $e_k^{(i,j,F)} \in \{i, j\}$  for every  $k = 1, 2, \dots, s$  and  $e_k^{(i,j,F)} = i$  if and only if  $k \in F$ .

We assign the weights as follows:  $w(e^i) = 1$  for every  $i = 1, 2, \dots, n$ ,  $w(e^{(i,j,F)}) = 2$  for each of the  $2^{s-1} - 1$  sets  $F$  and  $1 \leq i \neq j \leq n$  and  $w(e) = 0$  for every vector  $e \in X$  that has at least three coordinates of different value. Let  $F_0$  be the first set  $F$  chosen by MDV. Observe that for  $F_0$  MDV outputs the trivial assignment  $e^1, \dots, e^n$ , which is the best among  $n!$  assignments.

For every other  $F$  MDV outputs the trivial assignment which is better than  $n! - 1$  assignments. Further iteration will output the trivial assignment as well. Thus, we conclude that the trivial assignment is the best among at most  $(2^{s-1} - 1)(n! - 1) + 1$  assignments considered by MDV and, hence, the domination number of MDV is at most  $(2^{s-1} - 1)(n! - 1) + 1$ .

Now consider the last iteration of MDV. No improvement is made, and, thus, a solution with which we started the iteration will not change during the iteration. By permuting the elements of  $X_2, X_3, \dots, X_s$  (recall that  $X = X_1 \times X_2 \times \dots \times X_s$ ), if needed, we may assume, without loss of generality, that the solution at the start of the last permutation is the trivial assignment. Since  $e^{(i,j,F')} \neq e^{(i,j,F'')}$  provided  $F' \neq F''$  and  $F' \neq \{1, 2, \dots, s\} \setminus F''$ , as above, we can see that the trivial assignment is the best among exactly  $(2^{s-1} - 1)(n! - 1) + 1$  distinct assignments of the last iteration. Thus,  $(2^{s-1} - 1)(n! - 1) + 1$  is a lower bound on the domination number of MDV. Since this lower bound is also an upper bound on the domination number, we are done. □

This theorem and the result just after Theorem 10 show that ROM is of larger domination number than MDV for every fixed  $s \geq 3$  for every  $n$  large enough. This is in contrast with the experimental results reported in Section 6, where the solutions obtained by MDV are almost

always better than those produced by ROM. There is no contradiction in the two comparisons as they measure different sides of the quality of the two heuristics: the worst case behavior vs. the performance on some particular families of MAP instances.

## 5. Empirical evaluation of greedy like algorithms for TSP

We considered three ATSP heuristics in our experiments: *Greedy*, *NN*, and *Patch Cycles* (*Patch*) [22].

The *Greedy* heuristic is implemented as follows. Construct an array of all arcs  $x_i y_i$ ,  $x_i \neq y_i$ ,  $1 \leq i \leq n(n-1)$ , and sort this array by the arc weight:  $w(x_i y_i) \leq w(x_{i+1} y_{i+1})$  for every  $1 \leq i < n(n-1)$ . Let  $prev(i)$  be the vertex preceding the vertex  $i$  in the tour, and let  $next(i)$  be the vertex succeeding the vertex  $i$  in the tour. Initialize  $prev(i) = next(i) = 0$  for every  $1 \leq i \leq n$ . While the solution is incomplete, it consists of several separate components. For a vertex  $i$  let  $id(i)$  be the identifier of the vertex  $i$  component. Initialize  $id(i) = i$  for every  $1 \leq i \leq n$ . On every  $k$ th step of the heuristic try to add the arc  $x_k y_k$  to the current solution, i.e., check whether  $next(x_k) = 0$  and  $prev(y_k) = 0$  and  $id(x_k) \neq id(y_k)$ . If all the conditions are met, set  $next(x_k) = y_k$ ,  $prev(y_k) = x_k$ , and  $id(i) = id(y_k)$  for every  $i \in \{j : id(j) = id(x_k)\}$ . When  $n-1$  arcs are added to the solution, the algorithm closes the cycle and stops.

The details on the *NN* heuristic are available in Section 3.

The *Patch* heuristic proceeds as follows. Let  $\pi$  be a solution of the assignment problem (AP) for the distance matrix of ATSP. Construct vertex-disjoint cycles  $c^i$  based on the AP solution  $\pi$  such that  $c_{j+1}^i = \pi(c_j^i)$  for every  $1 \leq j < s_i$  and  $c_1^i = \pi(c_{s_i}^i)$ , where  $s_i$  is the number of vertices in the  $i$ th cycle. Let  $m$  be the number of cycles, such that  $\sum_{i=1}^m s_i = n$ . If  $m = 1$ , the cycle  $c^1$  is the optimal solution of ATSP and no further actions are required. Otherwise select two longest cycles (i.e., the cycles with the maximum values of  $s_i$ ) and patch them by removing edges  $x_1 x_2$  from the first of them and  $y_1 y_2$  from the second one such that the value  $w(x_1 y_2) + w(y_1 x_2) - w(x_1 x_2) - w(y_1 y_2)$  is minimized. Repeat this procedure until there is just one cycle, that is considered as a solution.

All the heuristics in this section and in Section 6 are implemented in Visual C++. The evaluation platform is based on AMD Athlon 64 X2 3.0 GHz processor.

The experiment results are reported in Tables 1 and 2. Table 1 includes the results for randomly generated instances of nine classes (for details see [13]). Ten instances of size 100, ten instances of size 316, three instances of size 1000, and one instance of size 3162 are considered for every instance class. The solution quality is presented by percent above the Held-Karp (HK) lower bound [20, 21].

Table 2 includes the results for several real-world ATSP instances from TSPLIB [24] and some other sources [20]. The solution quality is presented by percent above the best known solutions.

One can see that *Patch* clearly outperforms both *Greedy* and *NN* with respect to the solution quality, and the *NN* solutions are usually better than the *Greedy* ones (though *Greedy* slightly outperform *NN* on average with respect to the solution quality for the real-world instances). *NN* is much faster than both *Greedy* and *Patch*, while *Patch* is faster than *Greedy* for small instances and slower for the large ones. Johnson et al. [20] showed that, along with *Patch*, there are some other ATSP heuristics that are relatively fast and normally produce solutions that are much better than those obtained by *Greedy* and *NN*. (Some ATSP heuristics of good quality are also studied in [8].) Thus, it appears that *Greedy*

should never be used in practice and NN is of interest only if a very fast heuristic is required.

## 6. Empirical evaluation of greedy like algorithms for MAP

In this chapter we consider four MAP heuristics: Greedy, First Coordinate Fixing (FCF), Recursive Opt Matching (ROM), and Multi-Dimensionwise Variation (MDV).

Greedy proceeds as follows. Let  $A = \emptyset$  be a partial assignment and  $B$  an array of vectors. While  $|A| < n$ , i.e.,  $A$  is not a full assignment, the following steps are repeated. Scan the weight matrix to fill array  $B$  with  $k$  vectors corresponding to  $k$  minimal weights and sort  $B$  in non-decreasing order. For each vector  $e \in B$ , starting from the lightest, check whether  $A \cup \{e\}$  is a feasible partial assignment and, if so, add  $e$  to  $A$ . Note, that during the second and further cycles we scan not the whole weight matrix but only a subset  $X' \subset X$  of the vectors that can be included into the partial assignment  $A$  with the feasibility preservation:  $A \cup \{x\}$  is a partial assignment for any  $x \in X'$ . The size of the array  $B$  is calculated as  $k = \min\{128, |X'|\}$ .

The details on FCF, ROM and MDV heuristics are available in Section 4. As in [12], the number of MDV iterations was artificially restricted to 10.

The testbed includes three instance families: Random, Composite, and GP, discussed in [12].

In *Random Instance Family* (Random) the weight assigned to a vector is a random uniformly distributed integer value in the interval  $[a, b - 1]$ . We set  $a = 1$  and  $b = 101$ . It is proved (see [12]) that the optimal solutions of large Random instances are very likely to be of weight  $an$ , so we assume in our experiments that the optimal solutions of the considered Random instances are exactly  $n$ .

The *Composite Instance Family* (Composite) is a family of semi-random instances. They were introduced by Crama and Spieksma for 3-AP as a problem  $T$  [7]. We extend this family for  $s$ -AP.

Let  $d^1, d^2, \dots, d^s$  be  $n \times n$  matrices of non-negative uniformly distributed random integers in the interval  $[a, b - 1]$ . Let us consider a graph  $G(X_1 \cup X_2 \cup \dots \cup X_s, (X_1 \times X_2) \cup (X_2 \times X_3) \cup \dots \cup (X_{s-1} \times X_s) \cup (X_1 \times X_s))$ , where the weight of an edge  $(i, j) \in X_k \times X_{k+1}$  is  $d_{i,j}^k$  for  $1 \leq k < s$  and the weight of an edge  $(i, j) \in X_1 \times X_s$  is  $d_{i,j}^s$ . In this interpretation of  $s$ -AP, the objective is to find a set of  $n$  vertex-disjoint  $s$ -cycles  $C \subset X_1 \times X_2 \times \dots \times X_s$  such that the total weight of all edges covered by the cycles  $C$  is minimized.

In other words,  $w(e) = d_{e_1, e_2}^1 + d_{e_2, e_3}^2 + \dots + d_{e_{s-1}, e_s}^{s-1} + d_{e_1, e_s}^s$ .

The *GP Instance Family* (GP) contains pseudo-random instances with predefined optimal solutions. GP instances are generated by an algorithm given by Grundel and Pardalos [10]. The generator is naturally designed for  $s$ -AP for arbitrary large values of  $s$  and  $n$ . The GP generator is relatively slow and, thus, it was impossible to experiment with large GP instances.

The results of the experiments are reported in Tables 3, 4, and 5. One can see that Greedy is significantly slower than the FCF heuristic, while its solution quality is not significantly better than the FCF's one. ROM outperforms or have very close results to Greedy with respect to both the solution quality and the running times. MDV clearly outperforms all other heuristics with respect to the solution quality, and it is the fastest algorithm for

Random and Composite instances. For GP instances FCF and ROM are faster than MDV. Based on the experimental data, MDV is definitely the overall winner.

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| Family | <i>n</i> | Percents above HK |       |       | Running times, ms |       |          |
|--------|----------|-------------------|-------|-------|-------------------|-------|----------|
|        |          | Greedy            | NN    | Patch | Greedy            | NN    | Patch    |
| amat   | 100      | 176.4             | 203.7 | 11.1  | 2.03              | 0.04  | 0.28     |
|        | 316      | 246.1             | 231.3 | 6.5   | 25.97             | 0.45  | 2.91     |
|        | 1000     | 283.4             | 337.4 | 2.7   | 319.18            | 4.38  | 50.34    |
|        | 3162     | 344.1             | 397.3 | 1.9   | 3364.30           | 44.60 | 816.12   |
| coin   | 100      | 26.9              | 27.7  | 16.0  | 1.67              | 0.05  | 0.16     |
|        | 316      | 28.9              | 25.5  | 18.6  | 18.37             | 0.54  | 1.41     |
|        | 1000     | 26.9              | 25.2  | 17.4  | 208.20            | 4.30  | 34.18    |
|        | 3162     | 26.8              | 25.6  | 19.0  | 2382.02           | 46.26 | 431.35   |
| crane  | 100      | 30.1              | 43.0  | 9.3   | 2.12              | 0.05  | 0.38     |
|        | 316      | 45.3              | 60.0  | 13.6  | 26.03             | 0.46  | 8.92     |
|        | 1000     | 66.1              | 81.0  | 31.1  | 338.89            | 5.10  | 156.46   |
|        | 3162     | 105.9             | 113.2 | 58.4  | 3357.79           | 43.86 | 2366.64  |
| disk   | 100      | 99.2              | 90.2  | 6.7   | 1.98              | 0.04  | 0.21     |
|        | 316      | 148.7             | 107.7 | 2.2   | 26.37             | 0.40  | 5.72     |
|        | 1000     | 296.1             | 117.3 | 0.9   | 321.94            | 4.35  | 205.25   |
|        | 3162     | 566.5             | 162.0 | 0.3   | 3692.79           | 44.31 | 6935.62  |
| rtilt  | 100      | 318.5             | 28.5  | 17.9  | 2.57              | 0.04  | 0.70     |
|        | 316      | 651.6             | 28.2  | 17.9  | 26.59             | 0.41  | 10.06    |
|        | 1000     | 1219.4            | 27.9  | 19.5  | 391.19            | 5.46  | 259.75   |
|        | 3162     | 2260.9            | 24.2  | 21.3  | 3537.03           | 46.79 | 4477.49  |
| shop   | 100      | 48.1              | 16.7  | 1.2   | 2.03              | 0.04  | 1.37     |
|        | 316      | 55.9              | 14.8  | 0.6   | 20.90             | 0.43  | 26.89    |
|        | 1000     | 60.4              | 13.5  | 0.4   | 209.73            | 4.61  | 939.74   |
|        | 3162     | 63.8              | 11.9  | 0.2   | 2236.86           | 44.69 | 26662.96 |
| stilt  | 100      | 103.8             | 32.6  | 25.3  | 2.08              | 0.05  | 0.88     |
|        | 316      | 141.4             | 29.1  | 23.4  | 26.09             | 0.39  | 13.82    |
|        | 1000     | 166.3             | 27.2  | 25.2  | 315.08            | 5.03  | 156.53   |
|        | 3162     | 172.0             | 24.1  | 23.4  | 3428.08           | 44.22 | 2094.31  |
| super  | 100      | 3.9               | 8.0   | 1.8   | 0.65              | 0.04  | 0.17     |
|        | 316      | 4.1               | 8.8   | 2.7   | 6.70              | 0.94  | 2.55     |
|        | 1000     | 4.5               | 9.9   | 4.2   | 73.66             | 4.75  | 70.06    |
|        | 3162     | 4.9               | 10.1  | 6.1   | 815.01            | 61.75 | 959.90   |
| tmat   | 100      | 26.3              | 38.0  | 0.9   | 2.11              | 0.04  | 0.21     |
|        | 316      | 25.7              | 37.1  | 0.7   | 24.77             | 0.43  | 4.11     |
|        | 1000     | 24.7              | 37.8  | 0.2   | 220.47            | 4.23  | 75.23    |
|        | 3162     | 25.2              | 35.4  | 0.0   | 2041.57           | 45.73 | 1266.14  |
| Avg.   | 100      | 92.6              | 54.3  | 10.0  | 1.92              | 0.04  | 0.48     |
|        | 316      | 149.8             | 60.3  | 9.6   | 22.42             | 0.50  | 8.49     |
|        | 1000     | 238.7             | 75.2  | 11.3  | 266.48            | 4.69  | 216.39   |
|        | 3162     | 396.7             | 89.3  | 14.5  | 2761.72           | 46.91 | 5112.28  |

Table 1. ATSP heuristics experiment results for randomly generated instances.

| Instance | n   | Percents above BK |      |       | Running times, ms |       |       |
|----------|-----|-------------------|------|-------|-------------------|-------|-------|
|          |     | Greedy            | NN   | Patch | Greedy            | NN    | Patch |
| atex8    | 600 | 32.2              | 20.8 | 35.1  | 0.066             | 0.001 | 0.006 |
| big702   | 702 | 17.9              | 35.6 | 0.0   | 0.090             | 0.002 | 0.028 |
| code198  | 198 | ∞                 | ∞    | 14.0  | 0.002             | 0.000 | 0.001 |
| code253  | 253 | 59.0              | ∞    | 3.2   | 0.003             | 0.000 | 0.001 |
| dc112    | 112 | 1.3               | 1.6  | 0.2   | 0.001             | 0.000 | 0.001 |
| dc126    | 126 | 2.9               | 4.0  | 0.8   | 0.004             | 0.000 | 0.001 |
| dc134    | 134 | 0.9               | 1.7  | 0.0   | 0.002             | 0.000 | 0.001 |
| dc176    | 176 | 2.2               | 2.7  | 0.7   | 0.003             | 0.000 | 0.001 |
| dc188    | 188 | 1.4               | 2.3  | 0.1   | 0.003             | 0.000 | 0.001 |
| dc563    | 563 | 1.6               | 2.6  | 0.3   | 0.042             | 0.002 | 0.036 |
| dc849    | 849 | 0.3               | 0.7  | 0.0   | 0.050             | 0.003 | 0.143 |
| dc895    | 895 | 1.3               | 2.2  | 0.2   | 0.115             | 0.004 | 0.062 |
| dc932    | 932 | 0.9               | 1.4  | 0.2   | 0.105             | 0.003 | 0.061 |
| ftv100   | 101 | 60.6              | 44.1 | 1.9   | 0.002             | 0.000 | 0.000 |
| ftv110   | 111 | 38.1              | 47.2 | 2.5   | 0.002             | 0.000 | 0.000 |
| ftv120   | 121 | 45.3              | 38.8 | 6.6   | 0.002             | 0.000 | 0.000 |
| ftv130   | 131 | 40.2              | 32.9 | 3.8   | 0.002             | 0.000 | 0.000 |
| ftv140   | 141 | 38.1              | 42.2 | 3.5   | 0.003             | 0.000 | 0.000 |
| ftv150   | 151 | 43.2              | 36.4 | 2.6   | 0.003             | 0.000 | 0.000 |
| ftv160   | 161 | 50.4              | 51.5 | 1.7   | 0.003             | 0.000 | 0.000 |
| ftv170   | 171 | 42.8              | 42.4 | 2.0   | 0.004             | 0.000 | 0.001 |
| kro124p  | 100 | 21.0              | 31.1 | 13.8  | 0.002             | 0.000 | 0.000 |
| rbg323   | 323 | 7.9               | 30.8 | 0.0   | 0.011             | 0.000 | 0.007 |
| rbg358   | 358 | 8.0               | 55.8 | 0.0   | 0.012             | 0.000 | 0.009 |
| rbg403   | 403 | 0.8               | 43.4 | 0.0   | 0.014             | 0.001 | 0.010 |
| rbg443   | 443 | 0.7               | 44.2 | 0.0   | 0.021             | 0.001 | 0.012 |
| Avg.     |     | 20.8              | 25.7 | 3.6   | 0.022             | 0.001 | 0.015 |

Table 2. ATSP heuristics experiment results for real-world instances. Here ∞ stands for '> 10<sup>5</sup>' and BK for 'best known.'

| s    | n   | Percents above optimal |       |       |      | Running times, ms |       |        |       |
|------|-----|------------------------|-------|-------|------|-------------------|-------|--------|-------|
|      |     | Greedy                 | FCF   | ROM   | MDV  | Greedy            | FCF   | ROM    | MDV   |
| 3    | 100 | 101.0                  | 101.0 | 67.3  | 12.9 | 16.8              | 3.3   | 8.3    | 8.0   |
| 3    | 200 | 42.0                   | 50.5  | 15.5  | 0.1  | 112.9             | 29.2  | 69.8   | 29.6  |
| 3    | 300 | 27.2                   | 37.6  | 3.8   | 0.0  | 324.0             | 91.4  | 221.8  | 51.3  |
| 4    | 50  | 105.2                  | 181.0 | 128.2 | 34.2 | 72.9              | 18.4  | 49.4   | 4.9   |
| 4    | 80  | 74.0                   | 64.9  | 76.4  | 8.0  | 426.8             | 114.0 | 316.1  | 20.0  |
| 5    | 40  | 159.3                  | 139.5 | 168.8 | 29.5 | 1072.4            | 232.2 | 803.5  | 8.7   |
| 6    | 20  | 277.5                  | 302.5 | 327.0 | 41.0 | 693.8             | 156.1 | 509.1  | 3.8   |
| 7    | 12  | 420.8                  | 425.0 | 475.0 | 57.5 | 412.5             | 84.6  | 294.5  | 2.7   |
| 8    | 8   | 548.8                  | 550.0 | 723.8 | 62.5 | 207.2             | 44.3  | 152.2  | 2.2   |
| Avg. |     | 195.1                  | 205.8 | 220.6 | 27.3 | 371.02            | 85.95 | 269.41 | 14.57 |

Table 3. MAP heuristics experiment results for Random instances.

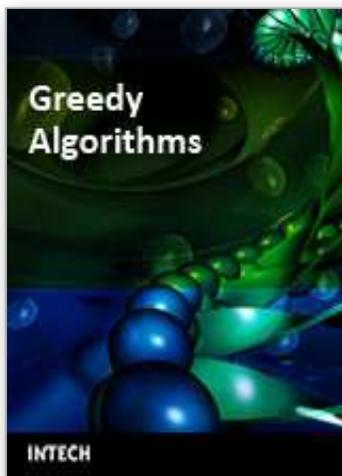
| $s$  | $n$ | Percents above best known |      |      |     | Running times, ms |       |        |       |
|------|-----|---------------------------|------|------|-----|-------------------|-------|--------|-------|
|      |     | Greedy                    | FCF  | ROM  | MDV | Greedy            | FCF   | ROM    | MDV   |
| 3    | 100 | 21.3                      | 38.1 | 15.9 | 0.0 | 15.9              | 3.6   | 8.9    | 12.0  |
| 3    | 200 | 19.3                      | 36.9 | 18.6 | 0.0 | 158.8             | 29.2  | 67.2   | 65.8  |
| 3    | 300 | 8.5                       | 22.8 | 14.6 | 0.0 | 644.3             | 92.5  | 221.7  | 160.3 |
| 4    | 50  | 32.3                      | 39.8 | 12.4 | 0.0 | 83.3              | 19.1  | 50.0   | 7.9   |
| 4    | 80  | 23.8                      | 36.7 | 7.8  | 0.0 | 588.1             | 118.8 | 312.7  | 27.9  |
| 5    | 40  | 28.9                      | 42.5 | 4.3  | 0.0 | 1350.9            | 241.6 | 932.5  | 11.4  |
| 6    | 20  | 35.3                      | 43.4 | 3.8  | 0.0 | 812.9             | 142.1 | 563.6  | 5.5   |
| 7    | 12  | 36.0                      | 43.8 | 5.7  | 0.0 | 504.1             | 85.0  | 294.8  | 4.0   |
| 8    | 8   | 28.5                      | 34.9 | 7.3  | 0.0 | 233.9             | 45.4  | 146.5  | 3.1   |
| Avg. |     | 26.0                      | 37.7 | 10.1 | 0.0 | 488.03            | 86.36 | 288.65 | 33.11 |

Table 4. MAP heuristics experiment results for Composite instances.

| $s$  | $n$ | Percents above optimal |      |      |     | Running times, ms |     |     |      |
|------|-----|------------------------|------|------|-----|-------------------|-----|-----|------|
|      |     | Greedy                 | FCF  | ROM  | MDV | Greedy            | FCF | ROM | MDV  |
| 3    | 50  | 9.9                    | 11.7 | 12.2 | 6.8 | 4.4               | 0.6 | 1.5 | 3.5  |
| 3    | 80  | 7.6                    | 8.2  | 11.6 | 4.5 | 22.0              | 2.0 | 4.9 | 13.3 |
| 3    | 100 | 5.6                    | 7.5  | 9.8  | 3.7 | 52.4              | 4.0 | 9.7 | 28.8 |
| 4    | 20  | 11.7                   | 12.2 | 5.3  | 6.8 | 7.0               | 0.7 | 1.6 | 0.9  |
| 4    | 30  | 8.8                    | 9.2  | 2.2  | 4.9 | 49.1              | 2.8 | 7.0 | 2.1  |
| 5    | 8   | 28.7                   | 25.9 | 17.6 | 8.8 | 1.2               | 0.2 | 0.3 | 0.4  |
| 5    | 12  | 12.8                   | 17.1 | 9.2  | 4.8 | 9.1               | 1.2 | 2.6 | 0.6  |
| 6    | 8   | 24.6                   | 20.1 | 13.6 | 3.3 | 6.5               | 0.9 | 2.6 | 0.7  |
| 7    | 5   | 27.0                   | 27.3 | 19.5 | 5.1 | 1.7               | 0.4 | 0.8 | 0.6  |
| 8    | 4   | 21.4                   | 30.2 | 28.1 | 5.2 | 1.9               | 0.3 | 0.8 | 0.7  |
| Avg. |     | 15.8                   | 16.9 | 12.9 | 5.4 | 15.5              | 1.3 | 3.2 | 5.2  |

Table 5. MAP heuristics experiment results for GP instances.

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