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A simulated annealing heuristic for the team orienteering problem with time windows

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ABSTRACT

This paper presents a simulated annealing based heuristic approach for the team orienteering problem with time windows (TOPTW). Given a set of known locations, each with a score, a service time, and a time window, the TOPTW finds a set of vehicle tours that maximizes the total collected scores. Each tour is limited in length and a visit to a location must start within the location's service time window. The proposed heuristic is applied to benchmark instances. Computational results indicate that the proposed heuristic is competitive with other solution approaches in the literature.

1. Introduction

In the team orienteering problem with time windows (TOPTW), a set of locations is given, each with a score, a service time and a time window. A fixed number of vehicle routes are constructed to collect scores from these locations. Each location can be visited at most once. The starting point and the end point of the routes are fixed. The time required to travel between each pair of locations is known in advance. The length of a route is limited by a common time limit. The objective of the TOPTW is to find a set of such routes that maximizes the total collected score.

The TOPTW is an extension of the widely studied team orienteering problem (TOP), which is itself an extension of the orienteering problem (OP). Vansteenwegen et al. (2011) provides an excellent review for OP and its extensions. Tang and Miller-Hooks (2005) also gives a detailed review on published solution approaches for the OP and the TOP. These problems have received much attention in the last few years due to their applications in practice and complexity in nature (Golden et al., 1987; Butt and Cavalier, 1994; Chao et al., 1996; Tang and Miller-Hooks, 2005; Montemanni and Gambardella, 2009; Vansteenwegen et al., 2009b; Tricoire et al., 2010).

The main contribution of this paper is an SA-based heuristic that can produce high quality TOPTW solutions. Many new best solutions are obtained by the proposed heuristic. For applications in which quick results are desired, a fast version of the proposed SA heuristic can be applied.

The remainder of this paper is organized as follows. In Section 2, problem definition and literature review are presented. The proposed simulated annealing heuristic for the TOPTW is described in Section 3. Section 4 describes the computational experiment in detail and discusses the computational results. Finally, conclusions and further research directions are discussed in Section 5.

2. Problem definition and literature review

The TOPTW can be defined on a directed network $G = (N,A)$, where $N = \{1,2,\ldots,n\}$ is the set of locations; $A = \{(i,j) : i \neq j \in N\}$ is the set of arcs connecting locations. Each location $i = 1,\ldots,n$ is associated with a score S_i, a service time T_i and a time window $[O_i,C_i]$. All paths must start at location 1 and end at location n. The time t_{ij} needed to travel from location i to j is known for each pair of locations i and j. The time of a path cannot exceed the given time limit T_{max}. Each location can be visited at most once. The visit must start within the location's time window. It is allowed to wait at a location before its time window starts. The objective is to determine a set of paths that maximizes the total collected score. Mathematical formulations for the TOPTW can be found in Vansteenwegen et al. (2009b) and Montemanni and Gambardella (2009).

The TOPTW is a highly constrained problem and very difficult to solve (Vansteenwegen et al., 2009b). Since the OP belongs to the class of NP-hard problems, it is unlikely that the TOPTW can be solved to optimality within polynomial time. For this reason, heuristic approaches seem to be the only viable way to tackle this problem.

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Although many efficient heuristic approaches for solving the TOP were proposed in the literature (Butt and Cavalier, 1994; Tang and Miller-Hooks, 2005; Archetti et al., 2007; Ke et al., 2008; Vansteenwegen et al., 2009a; Bouly et al., 2010; Souffriau et al., 2010), these approaches may not be able to solve the TOPTW efficiently. As pointed out by Vansteenwegen et al. (2009b), the local search moves used in these TOP solution methods are not as effective when applied to the TOPTW. However, so far, there is only little research devoted to the development of efficient solution approaches for the TOPTW. The best performing algorithms seem to be the ant colony system (ACS) approach by Montemanni and Gambardella (2009), the iterated local search (ILS) heuristic by Vansteenwegen et al. (2009b), and the variable neighborhood search (VNS) heuristic by Tricoire et al. (2010).

The ACS algorithm of Montemanni and Gambardella (2009) is based on the solution of a hierarchic generalization of the TOPTW. The ILS of Vansteenwegen et al. (2009b) is a simple, fast and effective solution approach for the TOPTW. The algorithm combines an insert move with a shake step to escape from local optimum. Although the solution quality of the ILS approach is not as good as that of the ACS algorithm, the computational time of ILS is significantly less than that of the ACS. The VNS heuristic of Tricoire et al. (2010) was originally designed for the multi-period orienteering problem with multiple time windows (MuPOPTW) but it was found to perform very well on the TOPTW.

3. Simulated annealing heuristic for the TOPTW

This research is motivated by the fact that there are only few efficient heuristic approaches proposed for the TOPTW in the literature. In particular, the current research develops a heuristic algorithm for the TOPTW based on the popular simulated annealing heuristic. Simulated annealing is a local search-based heuristic capable of escaping from being trapped into a local optimum by accepting, with small probability, worse solutions during its iterations. SA has been successfully applied to a wide variety of complex combinatorial optimization problems (Van Breedam, 1995; Chwif et al., 1998; Jayaraman and Ross, 2003; Lim et al., 2006; McKendall et al., 2006; Lin et al., 2009; Yu et al., 2010a,), as well as various real-world problems (Kim and Moon, 2003; Candalino et al., 2004; Lee et al., 2007).

The SA normally starts with a randomly generated initial solution. At each iteration, the algorithm selects a new solution from the neighborhood of the current solution. If the objective function value of the new solution is better than that of the current solution, the new solution replaces the current solution from which the search process continues. A new solution with a worse objective function value may also be accepted as the new current solution with a small probability. The essential idea is not to restrict the search moves only to better solutions. By accepting a worse solution, the procedure may escape from a local optimum. In the following subsections, the solution representation, neighborhood structure, parameters used in the proposed SA heuristic are discussed.

3.1. Solution representation

Before introducing our solution representation, it is necessary to point out the difference in data between the benchmark instances and the mathematical programming model described in Vansteenwegen et al. (2009b) and Montemanni and Gambardella (2009). In the original TOPTW, each vehicle travels along a path originating from node 1 and terminating at node n. However, in the benchmark problem sets available in the literature, a TOPTW path is often converted into a path that starts from and ends at a depot location. In other words, node 1 and node n are combined into a depot, while other nodes represent locations where scores may be collected. The maximum time limit of a path is translated into the latest start time of the depot's time window.

Keeping these in mind, a TOPTW solution is represented by a string of numbers consisting of a permutation of n locations, denoted by the set $\{1,2,\ldots,n\}$, and $m-1$ zeros that are used to separate tours. The jth non-zero number indicates the jth location to be visited. Thus, the first nonzero element in a solution indicates the first location to be visited in the first tour. Other locations are added to the tour one by one from left to right to represent the sequence in which they are visited, provided that the time window constraint of depot and each location on the tour is not violated. If adding a location to the tour violates the location's service time window or the depot's time window, the location is discarded, and the next location will be taken under consideration. A zero in the solution representation indicates that the next location to be visited is the depot. Thus, the current tour will be terminated and a new tour will be constructed whenever feasible.

A visit to a location must start within the location's service time window. If a vehicle arrives at the location earlier than the location's time window, it must wait until the time window starts. It can be verified that this solution representation always gives a feasible TOPTW solution without violating the time window constraint of locations and the time limit of tours.

3.2. Illustration of solution representation

Table 1 gives a TOPTW instance with 25 locations which can be serviced by two tours. Each location's coordinate (X,Y), service time (ST), score (S), earliest time (ET) and latest time (LT) of service time window are listed in the table. A sample solution to this instance is shown in Fig. 1, in which one $(m-1=2-1=1)$ dummy zero is introduced. The Euclidean distance is used and rounded down to

Table 1
A TOPTW instance with 25 locations served by two tours.

No.	*X*	*Y*	*ST*	*S*	*ET*	*LT*
0	40	50	–	–	0	240
1	25	60	10	20	190	211
2	22	55	10	30	50	80
3	20	50	10	10	109	139
4	20	60	10	40	145	175
5	20	45	10	20	21	50
6	18	25	10	20	95	125
7	15	25	10	20	79	109
8	15	60	10	30	141	171
9	10	35	10	20	91	121
10	14	40	10	30	119	149
11	8	10	10	40	79	89
12	8	45	10	20	64	94
13	50	40	10	10	142	172
14	55	45	10	10	135	165
15	22	40	10	20	58	88
16	10	20	10	20	72	102
17	10	45	10	20	149	179
18	40	10	10	20	40	77
19	45	10	10	40	72	102
20	42	35	10	10	172	182
21	40	15	10	10	67	97
22	30	15	10	40	92	122
23	35	35	10	30	65	95
24	30	25	10	10	148	178
25	25	15	10	20	154	184

5	2	7	15	9	10	23	8	12	4	13	14	1	0	18	19	22	11	21	6	25	16	17	3	24	20

Fig. 1. An example of solution representation.

the first decimal. A visual illustration of this solution representation is given in Fig. 2.

In this example, the first tour starts by servicing location 5 and then servicing locations 2, 7, 9, 10, 8, 4 and 1, followed by a zero. Thus, the tour will terminate after finishing servicing location 1. Because servicing locations 15, 23, 12, 13 and 14 will violate the time window constraint, these locations are excluded from the first tour.

The first location to be serviced in the second tour is location 18, followed by locations 19, 22, 6, 25 and 24. After finishing servicing location 24, this tour will return to the depot since no other locations can be visited. Location 11, 21, 16, 17, 3 and 20 are excluded from the second tour because of time window constraint.

The solution representation determines the locations of each tour. Thus, it is easy to calculate the objective function value (total score), denoted by obj(X), of a given solution X.

3.3. Neighborhood

This research uses a standard SA procedure with a random neighborhood structure that features three types of moves: swap, insertion, and inversion, to solve the TOPTW. Let $N(X)$ denote the set of neighboring solutions of the current solution X. At each iteration, a new feasible solution Y is selected from $N(X)$ by one of the three types of move as follows.

The swap move randomly selects the ith and the jth locations of X and then exchanges their positions. The insertion move is carried out by randomly selecting the ith location of X and then inserting it into the position immediately before another randomly selected jth location of X. The inversion move is performed by randomly selecting two locations, and then reversing the sequence between the two locations (including the two selected locations). The probabilities of performing the three moves: swap, insertion, and inversion are set to be 1/3, 1/3, and 1/3, respectively. Note that after a move, the tours need to be recalculated as illustrated in the previous section. Thus, a location that was not selected in the original solution may become a selected location after a move, and vice versa. The new solution is always feasible due to our solution representation scheme.

3.4. Parameters used

The proposed SA heuristic requires five parameters I_{iter}, T_0, $MaxT$, $N_{non\text{-}improving}$ and α. I_{iter} denotes the number of iterations the search proceeds at a particular temperature. T_0 represents the initial temperature. $MaxT$ is the maximal allowable computational time used. $N_{non\text{-}improving}$ is the maximum allowable number of temperature reductions during which the best objective function value is not improved. Finally, α is a coefficient used to control the speed of the cooling schedule.

3.5. The SA procedure

At the beginning, the current temperature T is set to be T_0 and an initial solution X is randomly generated. The solution consists of a random sequence of all locations and the $m - 1$ zeros. The current best solution X_{best} and the best objective function value obtained so far, denoted by F_{best}, are set to be X and obj(X), respectively.

At each iteration, a new solution Y is generated from the neighborhood of the current solution X, $N(X)$, and its objective function value is evaluated. Let Δ = obj(Y) − obj(X). If Δ is greater than or equal to zero (i.e., Y is better than X), X is replaced with Y. Otherwise, the probability of replacing X with Y is $\exp(\Delta/T)$. X_{best} and F_{best} record the best solution and the best objective function value obtained so far, as the algorithm progresses.

The current temperature T is decreased after I_{iter} iterations after the previous temperature decrease, according to the formula $T = \alpha T$, $0 < \alpha < 1$. After each temperature reduction, a local search procedure is used to improve X_{best}, the best solution found so far. The local search procedure first applies all possible swap moves to X_{best}. The best solution obtained from all possible swap moves

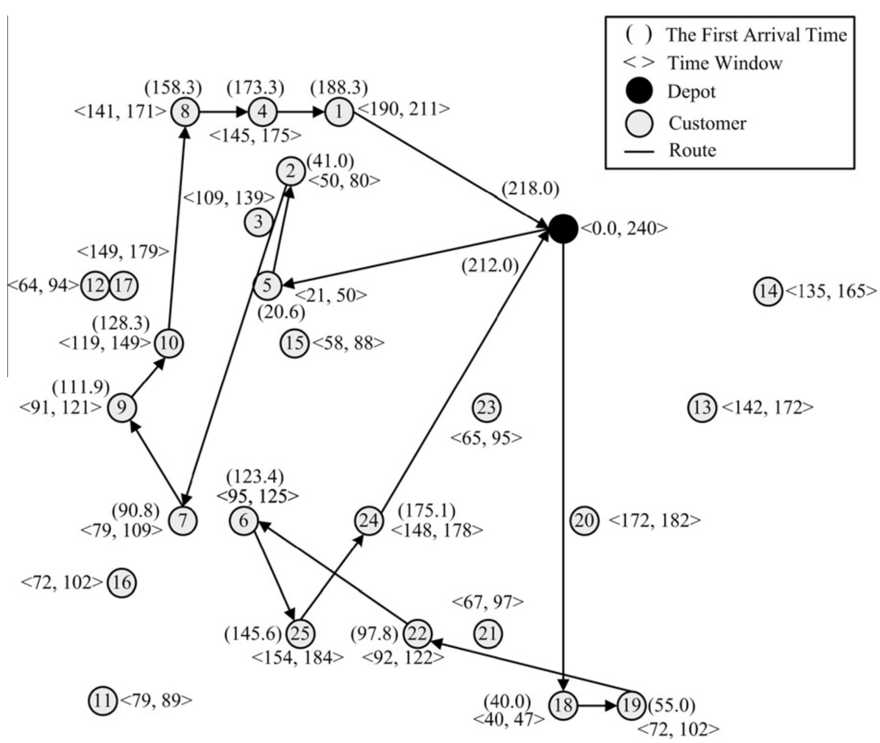

Fig. 2. A visual illustration of the example solution given in Fig. 1.

replaces X_{best} provided that it is better than X_{best}. Then all possible insertion moves are applied to X_{best}. Similarly, the best solution obtained from all possible insertion moves is used to replace X_{best} if it is better than X_{best}.

The algorithm is terminated when the current best solution X_{best} has not improved for $N_{non\text{-}improving}$ consecutive temperature decreases or the computational time used is equal to a *MaxT*. Based on the termination condition used, our simulated annealing algorithm has two variants. The version that uses *MaxT* as the termination condition is called the fast simulated annealing (FSA), while the one that uses $N_{non\text{-}improving}$ is called the slow simulated annealing (SSA). Following the termination of SA procedure, the best TOPTW solution can be derived from X_{best}. A flowchart depicting the proposed SA heuristic is given in Fig. 3.

4. Computational study

The proposed SA heuristic was coded in C language and run on a personal computer with an Intel Core 2 2.5 GHz CPU, which is

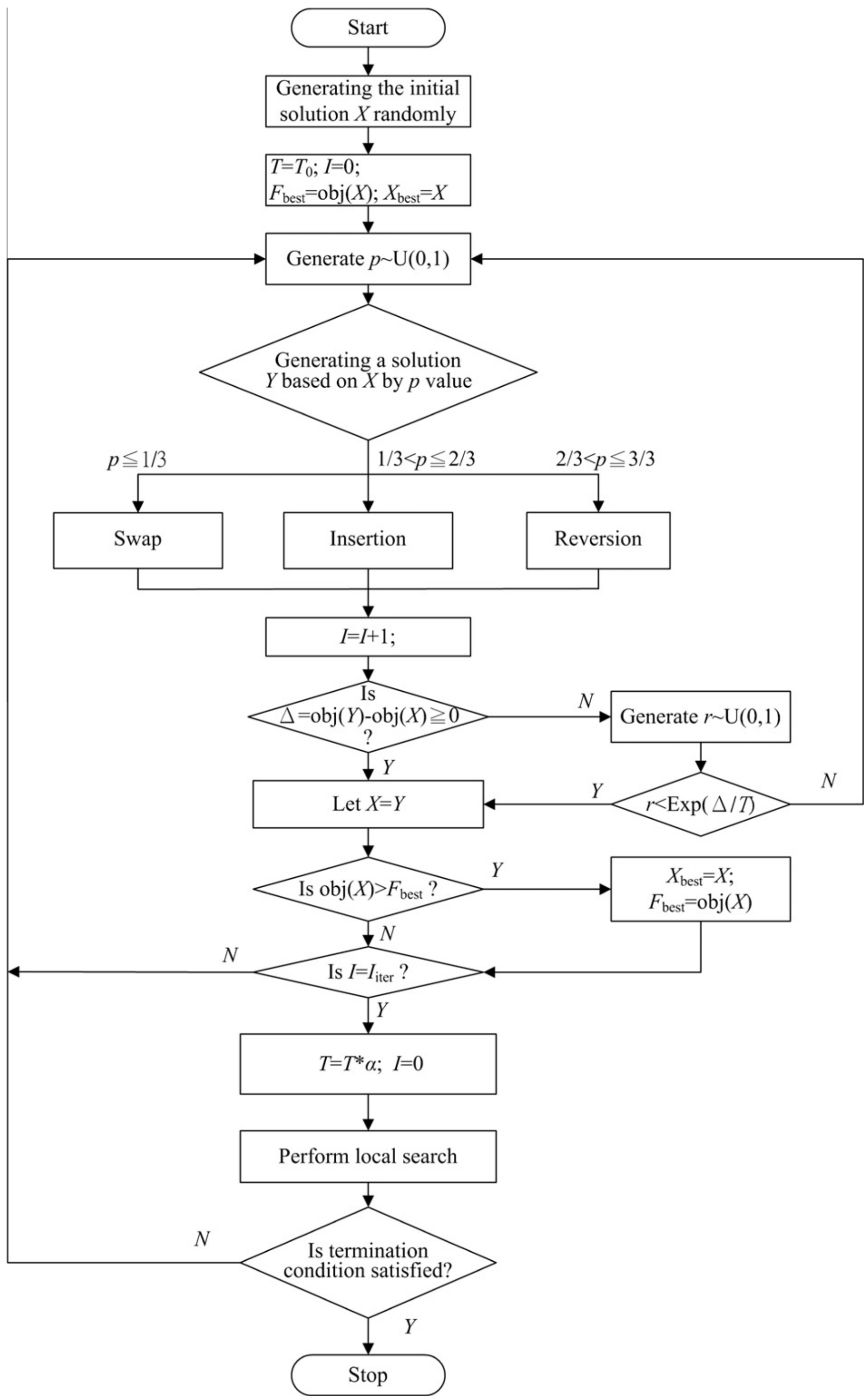

Fig. 3. A flowchart for the proposed SA heuristic.

comparable to the computational environment employed by Montemanni and Gambardella (2009) and Vansteenwegen et al. (2009b). The performance of the SA heuristic is compared with that of other existing state-of-the-art algorithms, namely the ACS based heuristic proposed by Montemanni and Gambardella (2009), the ILS based heuristic proposed by Vansteenwegen et al. (2009b), and the VNS heuristic proposed by Tricoire et al. (2010).

4.1. Test problems

The test problems used in the computational study are taken from Righini and Salani (2009), Montemanni and Gambardella (2009), and Vansteenwegen et al. (2009b). These benchmark instances can be downloaded from http://www.mech.kuleuven.be/en/cib/op.

The 58 OPTW instances created by Righini and Salani (2009) are converted from 48 Solomon's dataset of vehicle routing problem with time windows (c*_100, r*_100 and rc*_100) (Solomon, 1987) and 10 Cordeau et al.'s multi-depot vehicle routing problems (pr1–pr10) (Cordeau et al., 1997). Montemanni and Gambardella (2009) created 37 OPTW instances. Among them, 27 instances are converted from Solomon's dataset (c*_200, r*_200 and rc*_200) and 10 instances are converted from Cordeau et al.'s dataset (pr11–pr20). Each Solomon's instance has 100 possible visits. In Cordeau et al.'s dataset, the number of possible visits ranges from 48 to 288. Furthermore, Montemanni and Gambardella (2009) designed new TOPTW instances by increasing the number of tours in the aforementioned OPTW instances to two, three and four.

In order to evaluate the performance of their ILS approach, Vansteenwegen et al. (2009b) constructed a new TOPTW dataset consisting of more difficult instances with known optimal solution. This dataset uses the original instances from Solomon (1987) and Cordeau et al. (1997), but sets the number of tours to be the number of vehicles. Thus, the optimal objective value is the sum of all scores since it is feasible to visit all the locations. Problems pr11 to pr20 are not used because there are multiple depots in these instances. It is worth mentioning that in the computational study, the Cordeau et al.'s (1997) instances are used with a Euclidean distance rounding to the second decimal, while the distance used for other instances is Euclidean distance rounded to the first decimal.

4.2. Computational results

Parameter selection may influence the quality of the results. Five instances were randomly selected from each of the four problem sets ($m = 1,2,3,4$) for preliminary testing. The following combination of parameters were tested on these 20 test instances: $T_0 = 0.1$, 0.2, 0.3, 0.4, 0.5, 1.0, 1.5; $\alpha = 0.90$, 0.93, 0.95, 0.97, 0.99, 0.995, 0.999; $N_{non\text{-}improving} = 5$, 10, 20, 30, 40, 50; $I_{iter} = (n + m - 1) \times B$, where $B = 1000$, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10,000 and n and m are respectively the number of locations and tours. Based on the preliminary testing, the following parameter values seem to have the best performance within a reasonable computational time: $T_0 = 0.3$, $B = 8000$, $\alpha = 0.99$, $N_{non\text{-}improving} = 30$ for the SSA version; $T_0 = 0.1$, $B = 3000$, $\alpha = 0.999$, for the FSA version. The *MaxT* used in the termination condition of the FSA version equals to the running time of Vansteenwegen et al.'s ILS heuristic (2009b). Therefore, these parameters were adopted for all subsequent experiments in this study.

It was observed that when I_{iter} or $N_{non\text{-}improving}$ is increased, better solutions can be obtained at the expense of higher computational time. It is difficult to assess the effect of T_0 and α separately. In general, if the initial temperature T_0 is too high, more computational time is needed to obtain good solutions. On the other hand, if T_0 is too low, the proposed approaches tend to converge prematurely because of the low probability of accepting worse solutions. However, combinations of parameters do have significant impact on the solution quality. For example, setting $N_{non\text{-}improving} = 5$, $B = 3000$ for the SSA, the difference in the objective values obtained by different combinations of T_0 and α can be as large as 8.57% of the best-known solution value for the pr01 instance. The average percentage deviation of the solutions can be as large as 2.13%, compared to the solutions obtained by using the best combination of parameters. On average, this deviation is about 0.37%. For the FSA, the average percentage deviation of the solutions can be as large as 1.48%, compared to the solutions obtained by using the best combination of parameters. On average, this deviation is about 0.70%.

The computational time used for FSA is purposely set to be the running time of Vansteenwegen et al.'s ILS heuristic (2009b) so that the two approaches can be compared on the same base. The computational time for the SSA is larger than that of FSA in most cases. Therefore, better results can be obtained by the SSA. The better results can be used to compare with those of Montemanni and Gambardella's ACS algorithm (2009) and Tricoire et al.'s VNS algorithm (2010), which finds better solutions at the expense of higher computational time.

Tables 2–11 compare the scores obtained by the ACO of Montemanni and Gambardella (2009), the ILS of Vansteenwegen et al. (2009b), the VNS of Tricoire et al. (2010), the FSA, and the SSA. In Tables 2–5 and 7–11, column one (Name) denotes the instance's name. Column two (BKS) is the best known solution obtained by the ACO, the ILS or the VNS. It should be noted that the ILS, the FSA, and the SSA were executed only once, the ACO was executed 5 runs, and the VNS was executed 10 runs.

The third column (ACO) and the fourth column present the average score of five runs obtained by the ACO heuristic and the average computational time for the five runs. The fifth column (ILS) and the sixth column are the score obtained by the ILS heuristic and its computational time. The seventh column (VNS) and the eighth column are the average score of 10 runs obtained by the VNS heuristic and the average computational time for the 10 runs. The ninth column (FSA) and the tenth column present the best score obtained by the FSA heuristic and the computational time used. The 11th column (SSA) and the 12th column present the best score obtained by the SSA heuristic and the computation time. All computational time are measured in seconds. Bold numbers indicate that a new best-known solution is found. In the last row of these tables, the average relative percent deviation (ARDP) of each approach is calculated. The relative percentage deviation is the gap between the best-known solution and the obtained solution.

It can be seen from Tables 2–5, for Solomon's test problems (with $m = 1, 2, 3, 4$), the ARPD for the FSA ranges from 0.00% to 3.63%. This indicates that the FSA can produce good solutions at a small computational cost. The ARPD for the SSA ranges from 0.00% to 0.66%, indicating that the quality of the solutions obtained by the SSA is very close to that of the best-known solutions reported in the literature. Moreover, the SSA obtains best solutions for 146 problems out of the 224 problems in the four datasets, including 18 new best solutions.

As shown in Table 6, for problems in the Solomon's new dataset whose optimal solutions are known, the ARPDs of the FSA are only 1.64% and 0.40% for c*/r*/rc*_100 problems and c*/r*/rc*_200 problems, respectively. Meanwhile, the ARPDs of the SSA are only 0.59% and 0.08% for c*/r*/rc*_100 problems and c*/r*/rc*_200 problems, respectively. It reveals that both the FSA and the SSA approach can obtain near optimum solutions.

As can be seen from Tables 7–10, for the test problems of Cordeau et al. (with $m = 1, 2, 3, 4$), the ARPD for the FSA ranges from 3.49% to 8.83%. Therefore, the FSA can obtain good solutions in a short period of time for these problems. The ARPD for the SSA ranges from 0.63% to 2.77% indicating the effectiveness of the

Table 2
Results for the test problems of Solomon ($m = 1$).

Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)	Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)
c101	320	320.0	0.5	320	0.4	320.0	72.2	320	0.4	320	20.4	c201	870	870.0	507.8	840	1.1	870.0	507.8	870	1.1	870	28.3
c102	360	360.0	0.7	360	0.3	360.0	102.2	360	0.3	360	20.7	c202	930	928.0	454.8	910	2.8	928.0	454.8	930	2.8	930	33.5
c103	400	400.0	16.9	390	0.5	398.0	106.2	390	0.5	400	24.2	c203	960	960.0	614.3	940	1.7	960.0	614.3	940	1.7	960	59.6
c104	420	420.0	33.5	400	0.3	418.0	124.3	410	0.3	420	21.9	c204	980	972.0	484.0	950	1.6	972.0	484.0	950	1.6	970	42.3
c105	340	340.0	0.9	340	0.3	340.0	87.1	330	0.3	340	20.6	c205	910	908.0	645.4	900	1.2	908.0	645.4	900	1.2	910	46.9
c106	340	340.0	1.0	340	0.3	340.0	86.7	340	0.3	340	20.3	c206	930	927.0	616.5	910	1.6	927.0	616.5	920	1.6	930	29.0
c107	370	370.0	2.1	360	0.3	370.0	88.7	370	0.3	370	20.5	c207	930	930.0	599.5	910	2.1	930.0	599.5	930	2.1	930	29.1
c108	370	370.0	0.8	370	0.3	370.0	99.3	370	0.3	370	20.5	c208	950	949.0	558.9	930	1.6	949.0	558.9	940	1.6	950	31.2
c109	380	380.0	0.8	380	0.3	380.0	118.7	380	0.3	380	20.5	r201	797	796.7	1021.7	788	1.2	796.7	1021.7	772	1.2	794	51.1
r101	198	198.0	0.1	182	0.1	198.0	49.9	198	0.1	198	19.7	r202	915	905.6	1057.5	880	1.4	905.6	1057.5	878	1.4	914	46.4
r102	286	286.0	11.1	286	0.2	285.2	77.9	282	0.2	286	21.0	r203	1016	1007.9	1139.9	980	1.6	1007.9	1139.9	988	1.6	997	44.2
r103	293	292.6	640.6	286	0.2	293.0	90.2	293	0.2	293	20.3	r204	1081	1076.3	1253.5	1073	1.7	1076.3	1253.5	1059	1.7	1058	39.7
r104	303	303.0	164.0	297	0.2	303.0	95.9	294	0.2	303	23.2	r205	953	952.6	745.1	931	1.4	952.6	745.1	936	1.4	946	37.8
r105	247	247.0	3.0	247	0.1	247.0	85.4	247	0.1	247	20.3	r206	1022	1014.0	1168.1	996	1.5	1014.0	1168.1	950	1.5	1020	40.9
r106	293	293.0	86.3	293	0.2	292.2	89.6	270	0.2	293	22.1	r207	1072	1061.5	1065.3	1038	2.0	1061.5	1065.3	1033	2.0	1069	52.5
r107	299	294.6	922.6	288	0.2	299.0	105.5	277	0.2	297	21.5	r208	1112	1101.5	1160.8	1069	1.6	1101.5	1160.8	1066	1.6	1079	35.8
r108	308	306.0	696.1	297	0.2	308.0	119.1	294	0.2	306	40.6	r209	950	947.8	925.9	926	2.4	947.8	925.9	914	2.4	945	61.6
r109	277	277.0	28.0	276	0.2	277.0	77.4	264	0.2	277	20.4	r210	978	975.9	1065.6	958	1.9	975.9	1065.6	975	1.9	973	53.6
r110	284	283.2	617.6	281	0.3	284.0	86.0	282	0.3	284	20.8	r211	1042	1024.2	1120.7	1023	1.6	1024.2	1120.7	1023	1.6	1041	40.5
r111	297	296.6	484.4	295	0.2	297.0	95.4	286	0.2	297	27.9	rc201	795	795.0	640.8	780	1.0	795.0	640.8	781	1.0	795	44.4
r112	298	297.4	947.1	295	0.2	297.9	97.0	284	0.2	298	22.3	rc202	936	925.6	951.5	882	1.3	925.6	951.5	866	1.3	930	46.3
rc101	219	219.0	0.2	219	0.2	219.0	61.3	216	0.2	219	19.8	rc203	1003	988.2	938.4	960	2.7	988.2	938.4	956	2.7	967	32.4
rc102	266	266.0	30.9	259	0.2	266.0	53.3	249	0.2	266	20.2	rc204	1136	1120.8	970.3	1117	2.3	1120.8	970.3	1061	2.3	**1140**	46.5
rc103	266	266.0	57.2	265	0.3	266.0	62.9	265	0.3	266	20.7	rc205	857	845.9	726.6	840	1.0	845.9	726.6	800	1.0	854	52.6
rc104	301	301.0	29.4	297	0.3	301.0	58.0	263	0.3	301	27.5	rc206	895	878.4	838.7	860	1.1	878.4	838.7	866	1.1	885	60.2
rc105	244	244.0	9.7	221	0.2	244.0	78.6	219	0.2	244	20.3	rc207	983	960.8	893.5	926	1.3	960.8	893.5	899	1.3	977	68.4
rc106	252	252.0	308.6	239	0.2	252.0	71.9	240	0.2	252	21.0	rc208	1053	1043.5	995.5	1037	2.3	1043.5	995.5	1015	2.3	1041	51.2
rc107	277	277.0	502.1	274	0.2	277.0	69.6	244	0.2	277	22.0												
rc108	298	298.0	207.5	288	0.2	297.0	66.1	263	0.2	298	26.0												
Ave time			200.1		0.2		85.4		0.2		22.3				1193.4		1.7		857.8		1.7		44.7
Ave RDP			0.01		1.94		0.07		3.63		0.05				1.88		2.69		0.71		3.16		0.66

Table 3
Results for the test problems of Solomon ($m = 2$).

Name	BKS	ACO	*T* (s)	ILS	*T* (s)	VNS	*T* (s)	FSA	*T* (s)	SSA	*T* (s)
c101	590	588.0	110.8	590	1.4	587.0	83.8	590	1.4	590	26.2
c102	660	660.0	1427.4	650	0.9	653.0	100.0	660	0.9	660	26.5
c103	720	710.0	938.9	700	1.2	717.0	93.8	720	1.2	720	26.8
c104	760	754.0	1355.0	750	1.5	759.0	96.7	740	1.5	760	28.0
c105	640	640.0	1436.6	640	0.8	640.0	68.9	640	0.8	640	26.1
c106	620	620.0	104.6	620	0.8	620.0	95.8	620	0.8	620	25.6
c107	670	670.0	76.0	670	1.4	669.0	92.5	670	1.4	670	26.3
c108	680	680.0	95.3	670	0.8	680.0	89.7	660	0.8	680	26.2
c109	720	720.0	1817.3	710	0.9	719.0	70.6	720	0.9	720	26.1
r101	349	349.0	36.5	330	0.4	349.0	35.3	344	0.4	349	25.0
r102	508	506.6	2006.6	508	0.9	498.5	64.1	497	0.9	508	43.9
r103	522	518.8	1095.1	513	0.9	515.4	51.0	505	0.9	519	32.3
r104	549	540.0	2291.8	539	1.5	542.5	66.9	523	1.5	548	29.1
r105	453	453.0	1037.3	430	0.8	451.5	66.8	439	0.8	453	25.4
r106	529	523.8	2034.7	529	0.9	518.1	66.4	504	0.9	529	27.2
r107	535	527.4	2357.6	529	1.0	529.0	73.9	508	1.0	532	37.0
r108	556	553.6	1906.2	549	1.4	547.3	63.7	553	1.4	**558**	67.5
r109	506	505.4	1386.6	498	0.5	505.0	66.3	492	0.5	506	45.5
r110	525	523.4	1180.2	515	1.0	509.4	62.5	523	1.0	525	27.5
r111	544	535.6	1726.2	535	0.6	537.4	71.4	533	0.6	544	54.0
r112	544	541.6	1653.6	515	0.5	535.2	73.2	533	0.5	542	25.1
rc101	427	427.0	27.9	427	0.6	419.0	54.9	427	0.6	427	25.3
rc102	505	497.2	1496.9	494	0.8	504.1	61.1	480	0.8	505	42.4
rc103	524	510.2	1965.9	519	1.1	519.0	53.1	510	1.1	523	26.5
rc104	575	568.8	2381.3	565	0.7	568.2	53.0	558	0.7	575	63.1
rc105	480	478.4	1676.7	459	0.8	479.8	45.3	463	0.8	480	56.3
rc106	483	480.2	1865.1	458	0.6	477.9	57.5	467	0.6	483	47.3
rc107	534	530.2	771.5	515	0.5	519.3	63.2	489	0.5	529	26.8
rc108	556	541.6	821.0	546	0.6	535.8	53.2	509	0.6	554	36.1
Ave time			1278.6		0.9		68.8		0.9		34.5
Ave RDP			0.68		1.90		1.02		2.49		0.10

Name	BKS	ACO	*T* (s)	ILS	*T* (s)	VNS	*T* (s)	FSA	*T* (s)	SSA	*T* (s)
c201	1460	1452.0	508.6	1400	2.7	1447.0	634.5	1440	2.7	1450	64.3
c202	1460	1446.0	1568.2	1430	5.1	1457.0	658.7	1460	5.1	1460	50.2
c203	1480	1446.0	2334.8	1430	3.8	1471.0	568.9	1440	3.8	1450	39.4
c204	1480	1436.0	1373.2	1460	4.2	1480.0	420.3	1440	4.2	1450	38.9
c205	1460	1452.0	925.4	1450	3.1	1457.0	593.4	1450	3.1	**1470**	68.0
c206	1470	1460.0	1876.4	1440	2.8	1464.0	509.4	1460	2.8	1460	42.4
c207	1480	1452.0	1434.0	1450	3.2	1469.0	496.6	1450	3.2	1480	87.7
c208	1480	1462.0	1164.2	1460	2.8	1473.0	483.3	1460	2.8	1460	38.4
r201	1250	1236.0	2693.6	1231	2.1	1232.1	1401.6	1229	2.1	1242	73.7
r202	1338	1298.6	2482.2	1270	2.3	1333.5	1421.5	1319	2.3	1334	50.4
r203	1407	1349.4	3057.4	1377	1.9	1402.7	1148.4	1382	1.9	**1414**	196.2
r204	1458	1399.0	2713.5	1440	3.4	1455.3	785.2	1428	3.4	1447	70.9
r205	1378	1342.0	2593.7	1338	2.8	1366.8	1276.0	1350	2.8	1363	51.5
r206	1427	1373.8	2954.4	1401	2.8	1422.4	1015.9	1428	2.8	**1430**	113.7
r207	1458	1385.0	2624.1	1428	1.7	1453.6	723.2	1413	1.7	1452	158.8
r208	1458	1425.4	2828.9	1458	1.6	1458.0	448.7	1455	1.6	1457	56.0
r209	1405	1350.6	2988.9	1345	2.6	1393.0	1076.0	1372	2.6	1404	89.5
r210	1423	1355.4	2423.9	1365	1.9	1408.6	912.0	1379	1.9	1414	77.8
r211	1457	1403.0	2726.1	1422	1.9	1457.0	957.5	1416	1.9	1451	66.9
rc201	1376	1365.4	1654.3	1305	1.9	1359.7	897.1	1335	1.9	**1377**	73.3
rc202	1500	1464.8	2619.6	1461	2.1	1487.6	909.1	1461	2.1	1499	51.8
rc203	1621	1542.2	2176.2	1573	2.0	1593.4	821.0	1507	2.0	1576	94.9
rc204	1716	1614.8	2561.8	1656	2.1	1710.2	740.8	1633	2.1	1674	115.6
rc205	1455	1417.4	2115.2	1381	3.2	1436.3	766.8	1413	3.2	**1458**	50.5
rc206	1546	1495.6	2105.1	1495	1.9	1523.4	769.6	1491	1.9	1528	50.8
rc207	1566	1523.0	2937.5	1531	2.7	1552.2	835.9	1532	2.7	**1574**	73.5
rc208	1691	1608.4	2572.3	1606	1.7	1676.1	698.2	1630	1.7	1675	130.4
Ave time			222.7		2.6		813.7		2.6		79.6
Ave RDP			2.84		2.75		0.65		2.28		0.61

Table 4
Results for the test problems of Solomon ($m = 3$).

Name	BKS	ACO	*T* (s)	ILS	*T* (s)	VNS	*T* (s)	FSA	*T* (s)	SSA	*T* (s)	Name	BKS	ACO	*T* (s)	ILS	*T* (s)	VNS	*T* (s)	FSA	*T* (s)	SSA	*T* (s)
c101	810	810.0	1515.6	790	1.1	810.0	67.0	810	1.1	810	31.7	c201	1810	1810.0	259.2	1750	2.2	1810.0	256.5	1800	2.2	1800	48.1
c102	920	918.0	442.8	890	2.1	916.0	89.3	920	2.1	920	32.7	c202	1810	1784.0	1603.2	1750	2.0	1810.0	321.5	1750	2.0	1790	68.3
c103	980	972.0	1415.3	960	2.2	972.0	91.4	970	2.2	980	37.3	c203	1810	1738.0	1039.9	1760	2.0	1810.0	185.4	1740	2.0	1770	111.9
c104	1030	1004.0	681.7	1010	1.3	1020.0	78.9	1010	1.3	1010	33.1	c204	1810	1758.0	1025.8	1780	1.5	1810.0	201.6	1730	1.5	1750	54.5
c105	870	870.0	1010.0	840	1.0	858.0	93.8	860	1.0	870	32.9	c205	1810	1796.0	2007.3	1770	2.5	1809.0	236.6	1780	2.5	1810	42.5
c106	870	870.0	1132.3	840	1.1	867.0	89.5	860	1.1	870	39.6	c206	1810	1788.0	1862.0	1770	1.5	1810.0	265.9	1770	1.5	1780	40.8
c107	910	910.0	892.7	900	1.5	905.0	91.8	890	1.5	910	33.4	c207	1810	1784.0	1223.0	1810	3.4	1810.0	233.3	1770	3.4	1800	59.5
c108	920	912.0	971.2	900	1.2	913.0	85.3	900	1.2	920	33.1	c208	1810	1786.0	1542.7	1810	2.4	1810.0	231.8	1790	2.4	1800	52.2
c109	970	954.0	1327.5	950	2.0	967.0	82.3	950	2.0	970	43.5	r201	1436	1428.4	1400.0	1408	2.4	1428.2	814.4	1421	2.4	1429	50.3
r101	484	481.0	240.6	481	0.8	482.3	42.9	475	0.8	484	48.6	r202	1458	1445.6	1966.2	1443	2.7	1453.7	519.7	1455	2.7	1458	59.0
r102	691	682.0	2435.4	685	1.0	681.7	66.9	678	1.0	**694**	43.5	r203	1458	1452.4	2564.3	1458	1.6	1458.0	257.3	1458	1.6	1458	39.9
r103	747	729.8	2694.9	720	2.0	726.6	61.2	714	2.0	736	46.1	r204	1458	1458.0	174.7	1458	1.0	1458.0	211.7	1458	1.0	1458	38.4
r104	777	760.6	2531.4	765	1.5	759.7	60.2	754	1.5	777	71.2	r205	1458	1454.8	1830.7	1458	1.1	1458.0	296.3	1458	1.1	1458	39.3
r105	620	619.2	796.0	609	2.3	619.2	52.7	611	2.3	619	36.5	r206	1458	1456.8	1328.8	1458	1.1	1458.0	240.3	1458	1.1	1458	38.9
r106	726	715.0	755.5	719	2.1	717.4	65.7	719	2.1	**729**	38.6	r207	1458	1458.0	598.6	1458	1.0	1458.0	220.1	1458	1.0	1458	38.5
r107	760	751.6	1998.9	747	1.1	755.8	60.7	747	1.1	759	90.8	r208	1458	1458.0	425.6	1458	0.8	1458.0	216.6	1458	0.8	1458	38.4
r108	797	781.8	2388.5	790	3.1	781.2	70.9	751	3.1	789	81.8	r209	1458	1456.8	1163.7	1458	1.1	1458.0	272.0	1458	1.1	1458	40.1
r109	710	701.8	1098.8	699	1.8	703.9	64.0	695	1.8	702	40.2	r210	1458	1456.2	1428.1	1458	1.2	1458.0	289.9	1458	1.2	1458	40.0
r110	737	732.6	1708.5	711	1.4	721.9	63.5	705	1.4	734	36.8	r211	1458	1457.8	7.3	1458	1.0	1458.0	200.1	1458	1.0	1458	38.6
r111	773	755.4	1286.7	764	1.8	763.4	65.0	757	1.8	771	46.9	rc201	1698	1672.0	1084.9	1625	1.9	1689.4	786.6	1655	1.9	1681	98.3
r112	771	758.8	2091.2	758	1.1	760.0	69.2	732	1.1	**776**	91.8	rc202	1719	1701.4	2230.7	1686	1.7	1711.6	491.2	1690	1.7	1714	48.3
rc101	621	620.4	195.7	604	1.4	619.8	58.7	581	1.4	621	34.2	rc203	1724	1719.6	1213.2	1724	2.9	1724.0	313.9	1724	2.9	1724	39.1
rc102	711	698.8	1145.5	698	1.3	710.3	60.4	689	1.3	710	41.3	rc204	1724	1722.2	1261.3	1724	1.0	1724.0	222.8	1724	1.0	1724	38.3
rc103	747	741.4	2754.0	747	1.1	746.5	67.3	721	1.1	**764**	44.6	rc205	1709	1672.2	1439.8	1659	2.4	1696.7	573.2	1682	2.4	1709	122.3
rc104	833	813.2	2277.0	822	1.3	824.5	59.8	795	1.3	814	33.0	rc206	1724	1712.6	2185.2	1708	1.3	1724.0	339.9	1719	1.3	1724	46.0
rc105	682	677.8	1092.0	654	0.8	677.2	63.8	676	0.8	682	32.0	rc207	1724	1714.8	2553.9	1713	1.5	1724.0	295.1	1722	1.5	1724	40.4
rc106	705	692.4	1748.3	678	1.0	686.2	49.7	682	1.0	**706**	61.5	rc208	1724	1722.2	893.9	1724	1.1	1724.0	209.5	1724	1.1	1724	39.1
rc107	773	748.0	1158.5	745	0.9	761.6	58.2	751	0.9	773	43.8												
rc108	795	768.2	1443.7	757	1.1	778.0	66.9	757	1.1	778	52.0												
Ave time			1421.7		1.5		68.9		1.5		45.9				1345.0		1.7		322.3		1.7		52.2
Ave RDP			1.26		2.21		1.03		2.61		0.25				0.80		1.08		0.09		0.99		0.43

Table 5
Results for the test problems of Solomon ($m = 4$).

Name	BKS	ACO	*T* (s)	ILS	*T* (s)	VNS	*T* (s)	FSA	*T* (s)	SSA	*T* (s)	Name	BKS	ACO	*T* (s)	ILS	*T* (s)	VNS	*T* (s)	FSA	*T* (s)	SSA	*T* (s)
c101	1020	1018.0	1049.1	1000	3.8	1013.0	78.5	1020	3.8	1020	37.1	c201	1810	1810.0	1.2	1810	1.1	1810.0	92.5	1810	1.1	1810	44.9
c102	1150	1142.0	1211.3	1090	1.8	1139.0	90.1	1140	1.8	1150	40.0	c202	1810	1810.0	8.9	1810	1.1	1810.0	114.8	1810	1.1	1810	44.2
c103	1190	1186.0	2329.6	1150	2.5	1180.0	93.8	1180	2.5	1190	38.1	c203	1810	1810.0	43.9	1810	1.0	1810.0	84.7	1810	1.0	1810	42.0
c104	1260	1226.0	1493.9	1220	3.0	1248.0	79.7	1230	3.0	1230	41.0	c204	1810	1810.0	1.3	1810	1.0	1810.0	107.0	1810	1.0	1810	39.6
c105	1060	1052.0	716.5	1030	1.8	1055.0	85.0	1050	1.8	1060	36.8	c205	1810	1810.0	0.3	1810	1.0	1810.0	106.6	1810	1.0	1810	42.0
c106	1080	1058.0	556.8	1040	2.1	1062.0	82.2	1070	2.1	1080	69.0	c206	1810	1810.0	0.1	1810	1.0	1810.0	109.3	1810	1.0	1810	40.6
c107	1120	1114.0	411.3	1100	2.0	1108.0	83.3	1110	2.0	1120	45.5	c207	1810	1800.0	5.8	1810	1.0	1810.0	115.0	1810	1.0	1810	40.8
c108	1130	1112.0	820.1	1100	3.6	1123.0	70.4	1120	3.6	1130	69.1	c208	1810	1810.0	0.2	1810	0.8	1810.0	108.4	1810	0.8	1810	40.0
c109	1190	1172.0	916.0	1180	2.5	1174.0	73.8	1170	2.5	1190	69.0	r201	1458	1458.0	376.4	1458	1.3	1458.0	294.6	1458	1.3	1458	42.0
r101	611	608.0	55.1	601	1.4	610.2	40.4	605	1.4	611	33.8	r202	1458	1458.0	936.2	1458	1.1	1458.0	171.5	1458	1.1	1458	41.6
r102	840	825.6	1924.5	807	1.7	828.4	59.4	841	1.7	**843**	45.2	r203	1458	1458.0	73.9	1458	0.9	1458.0	137.3	1458	0.9	1458	40.2
r103	921	902.2	2622.2	878	2.2	909.9	68.8	898	2.2	**926**	97.1	r204	1458	1458.0	0.0	1458	0.6	1458.0	135.9	1458	0.6	1458	38.9
r104	972	944.2	2343.9	941	3.8	954.8	62.9	928	3.8	964	84.7	r205	1458	1458.0	1.3	1458	0.9	1458.0	153.6	1458	0.9	1458	39.6
r105	778	766.0	838.5	735	2.9	768.0	62.5	758	2.9	771	47.3	r206	1458	1458.0	0.0	1458	0.9	1458.0	131.9	1458	0.9	1458	39.4
r106	905	889.8	929.5	870	3.5	890.9	63.7	900	3.5	905	78.7	r207	1458	1458.0	0.0	1458	0.8	1458.0	111.9	1458	0.8	1458	38.7
r107	938	932.4	2660.9	927	3.3	930.4	62.6	926	3.3	**942**	42.0	r208	1458	1458.0	0.0	1458	0.5	1458.0	127.0	1458	0.5	1458	38.1
r108	994	976.2	2596.2	982	3.2	973.2	60.4	953	3.2	977	70.6	r209	1458	1458.0	0.0	1458	1.0	1458.0	139.0	1458	1.0	1458	39.6
r109	884	876.6	1374.5	866	2.1	870.5	55.3	846	2.1	**885**	68.0	r210	1458	1458.0	3.1	1458	0.9	1458.0	140.9	1458	0.9	1458	40.0
r110	914	900.0	926.3	870	2.0	898.1	70.7	868	2.0	893	39.5	r211	1458	1458.0	0.0	1458	0.7	1458.0	114.6	1458	0.7	1458	38.7
r111	949	932.4	1896.4	935	2.0	936.6	63.8	921	2.0	948	53.2	rc201	1724	1724.0	2327.4	1724	2.1	1724.0	231.9	1724	2.1	1724	41.7
r112	971	947.6	1662.6	939	3.1	964.4	63.6	946	3.1	958	40.5	rc202	1724	1724.0	1095.8	1724	1.1	1724.0	208.8	1724	1.1	1724	41.0
rc101	811	805.4	1324.3	794	1.9	777.2	55.3	806	1.9	808	44.3	rc203	1724	1724.0	308.6	1724	0.9	1724.0	157.5	1724	0.9	1724	39.8
rc102	903	899.4	2218.8	881	2.3	893.4	67.0	876	2.3	902	126.9	rc204	1724	1724.0	53.3	1724	0.8	1724.0	120.3	1724	0.8	1724	38.7
rc103	950	941.8	2005.2	947	2.0	945.4	64.1	936	2.0	**970**	70.0	rc205	1724	1724.0	1313.7	1724	2.1	1724.0	192.9	1724	2.1	1724	41.6
rc104	1059	1013.2	2139.3	1019	1.7	1033.5	64.8	1030	1.7	1059	75.3	rc206	1724	1723.6	2.8	1724	1.0	1724.0	145.5	1724	1.0	1724	39.8
rc105	875	867.2	1052.3	841	1.5	859.0	53.6	858	1.5	875	46.2	rc207	1724	1722.4	72.1	1724	1.0	1724.0	135.1	1724	1.0	1724	39.7
rc106	909	901.4	2106.7	874	2.5	894.4	49.6	891	2.5	901	41.4	rc208	1724	1724.0	0.0	1724	0.9	1724.0	124.3	1724	0.9	1724	38.9
rc107	980	959.2	1763.1	951	1.9	958.0	53.8	959	1.9	980	93.8												
rc108	1025	1000.2	2222.3	998	2.0	1011.5	59.6	963	2.0	1023	47.1												
Ave time			1523.0		2.4		66.8		2.4		58.3				245.4		1.0		141.2		1.0		40.4
Ave RDP			1.45		2.91		1.35		2.09		0.26				0.02		0.00		0.00		0.00		0.00

Table 6
Results for the test problems of Solomon (new data set).

Name	m	OPT	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)	Name	m	OPT	ILS	T (s)	FSA	T (s)	SSA	T (s)
c101	10	1810	1720	4.1	1809.0	21.7	1760	4.1	1770	89.5	c201	4	1810	1810	1.5	1810	1.5	1810	45.0
c102	10	1810	1790	4.2	1810.0	19.8	1800	4.2	1810	52.9	c202	4	1810	1810	1.1	1810	1.1	1810	44.3
c103	10	1810	1810	3.0	1810.0	18.8	1810	3.0	1810	52.9	c203	4	1810	1810	1.0	1810	1.0	1810	42.1
c104	10	1810	1810	1.8	1810.0	16.8	1810	1.8	1810	44.4	c204	4	1810	1810	1.0	1810	1.0	1810	39.8
c105	10	1810	1770	2.8	1810.0	22.7	1720	2.8	1780	152.7	c205	4	1810	1810	1.0	1810	1.0	1810	42.0
c106	10	1810	1750	3.8	1808.0	23.5	1710	3.8	1800	123.1	c206	4	1810	1810	1.0	1810	1.0	1810	40.7
c107	10	1810	1790	3.1	1810.0	21.9	1760	3.1	1760	61.1	c207	4	1810	1810	1.0	1810	1.0	1810	40.9
c108	10	1810	1810	2.5	1810.0	19.6	1750	2.5	1770	59.6	c208	4	1810	1810	0.9	1810	0.9	1810	40.1
c109	10	1810	1810	2.0	1810.0	16.1	1780	2.0	1810	63.0	r201	4	1458	1458	1.3	1458	1.3	1458	42.2
r101	19	1458	1441	2.5	1455.8	9.2	1453	2.5	1455	67.9	r202	3	1458	1443	2.7	1455	2.7	1458	58.5
r102	17	1458	1450	3.1	1451.1	9.6	1452	3.1	1458	84.9	r203	3	1458	1458	1.5	1458	1.5	1458	39.4
r103	13	1458	1450	2.0	1453.3	16.9	1450	2.0	1455	59.6	r204	2	1458	1440	3.3	1428	3.3	1447	70.2
r104	9	1458	1402	2.3	1443.5	28.7	1426	2.3	1442	131.3	r205	3	1458	1458	1.1	1458	1.1	1458	38.7
r105	14	1458	1435	4.1	1450.1	16.9	1455	4.1	1458	136.5	r206	3	1458	1458	1.0	1458	1.0	1458	38.4
r106	12	1458	1441	3.1	1451.9	20.2	1451	3.1	1458	116.3	r207	2	1458	1428	1.6	1413	1.6	1452	155.9
r107	10	1458	1431	3.3	1449.7	26.9	1433	3.3	1452	78.8	r208	2	1458	1458	1.6	1455	1.6	1457	54.2
r108	9	1458	1430	2.7	1453.2	26.6	1432	2.7	1447	87.1	r209	3	1458	1458	1.1	1458	1.1	1458	38.8
r109	11	1458	1432	2.5	1448.3	23.1	1432	2.5	1453	128.1	r210	3	1458	1458	1.2	1458	1.2	1458	39.0
r110	10	1458	1419	4.4	1450.5	26.4	1441	4.4	1454	172.9	r211	2	1458	1422	1.9	1416	1.9	1451	66.2
r111	10	1458	1410	3.0	1449.2	25.5	1440	3.0	1444	114.6	rc201	4	1724	1724	2.2	1724	2.2	1724	41.7
r112	9	1458	1418	2.4	1451.9	27.9	1416	2.4	1446	78.0	rc202	3	1724	1686	1.7	1690	1.7	1714	47.8
rc101	14	1724	1686	4.3	1704.5	18.4	1703	4.3	1712	79.9	rc203	3	1724	1724	2.8	1724	2.8	1724	38.7
rc102	12	1724	1659	2.9	1696.0	22.0	1683	2.9	1718	103.4	rc204	3	1724	1724	1.0	1724	1.0	1724	37.9
rc103	11	1724	1689	3.4	1715.8	22.1	1700	3.4	1724	82.6	rc205	4	1724	1724	2.1	1724	2.1	1724	41.4
rc104	10	1724	1719	3.2	1722.7	21.5	1707	3.2	1719	87.7	rc206	3	1724	1708	1.3	1719	1.3	1724	45.4
rc105	13	1724	1691	3.9	1698.2	18.1	1698	3.9	1716	87.0	rc207	3	1724	1713	1.4	1722	1.4	1724	39.7
rc106	11	1724	1665	4.8	1694.8	24.5	1687	4.8	1714	63.7	rc208	3	1724	1724	1.0	1724	1.0	1724	38.4
rc107	11	1724	1701	2.4	1721.0	19.8	1709	2.4	1722	51.4									
rc108	10	1724	1698	5.6	1721.8	21.7	1712	5.6	1719	121.0									
Ave time				3.2		20.9		3.2		90.7					1.5		1.5		48.4
Ave RDP				1.80		0.45		1.64		0.59					0.39		0.40		0.08

Table 7
Results for the test problems of Cordeau et al. ($m = 1$).

Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)	Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)
pro01	308	308.0	256.2	304	0.5	308.0	81.2	304	0.5	305	8.3	pro11	330	327.8	1743.7	330	0.3	328.0	131.4	339	0.3	**351**	10.3
pro02	404	403.8	1147.8	385	0.6	403.9	251.5	392	0.6	404	29.1	pro12	442	436.4	2017.6	431	0.9	442.0	309.6	432	0.9	430	26.3
pro03	394	394.0	2024.3	384	1.0	390.5	419.8	381	1.0	394	59.9	pro13	461	441.0	2312.7	450	1.9	453.7	514.1	424	1.9	452	49.0
pro04	489	482.6	1404.7	447	1.9	488.1	733.2	470	1.9	489	106.7	pro14	567	494.0	23.1	482	1.1	550.1	1163.8	499	1.1	540	134.3
pro05	595	576.8	2075.7	576	4.6	586.1	1663.2	527	4.6	589	281.7	pro15	678	524.8	18.2	638	5.3	663.2	1900.9	613	5.3	666	118.5
pro06	590	564.6	2199.8	538	2.5	588.2	1628.4	557	2.5	575	253.4	pro16	674	517.8	25.7	559	4.1	637.0	1854.1	562	4.1	616	558.0
pro07	298	298.0	20.1	291	0.4	297.5	141.5	289	0.4	298	15.0	pro17	359	358.0	1330.9	346	0.2	358.3	140.5	335	0.2	**362**	37.6
pro08	463	462.6	2476.0	463	1.0	452.2	450.2	438	1.0	462	76.0	pro18	535	488.8	1350.0	479	0.8	519.4	760.9	477	0.8	**539**	61.8
pro09	493	481.8	2318.2	461	1.4	481.5	1079.1	461	1.4	482	102.3	pro19	562	475.0	30.0	499	2.7	551.6	1242.2	501	2.7	531	152.9
pro10	594	588.4	2343.5	539	3.6	575.5	1772.4	539	3.6	578	189.7	pro20	662	552.4	24.6	570	2.5	647.8	2441.9	568	2.5	626	475.3
Ave time			1257.1		1.8		822.1		1.8		112.2				887.7		2.0		832.9		2.0		162.4
Ave RDP			1.20		4.72		1.08		5.26		0.97				10.59		8.20		1.99		8.83		2.28

SSA. The SSA obtains 15 new best solutions and 10 existing best-known solutions for the 80 problems in these datasets.

It can be seen from Table 11, for the test problems in the new data set converted from Cordeau et al.'s benchmark problems, the ARPDs of the FSA and the SSA are only 1.44% and 1.04%, respectively. Thus, both of the proposed FSA and SSA approaches can obtain near optimum solutions for these instances.

Table 12 compares the performance of our algorithms with the ACO, the ILS, and the VNS heuristics. It can be concluded that FSA's performance is worse than the ACO and the VNS, but slightly better than the ILS. For more than half of the datasets, the average gaps of the FSA are smaller than those of the ILS. It should be noted that the computational time of the ILS and the FSA are much less than the CPU time used by the ACO and the VNS heuristics. The performance of the SSA is clearly better than those of the ACO, the ILS, and the VNS. The average gaps of the SSA are smaller than or equal to those of the ACO and the VNS for most of the datasets.

Finally, the average computational time for the ACO, ILS, VNS, FSA, and SSA are displayed in Table 13. Although the computational time of the FSA is the same as that of the ILS, the solution quality of the FSA is slightly better than that of the ILS. It can also be seen that both the ILS and the FSA are many times faster than the ACO and the VNS, but the solution quality of these algorithms are very close to that of the ACO and the VNS. Although the computational time for the SSA is much longer than those of the FSA and the ILS, the solution quality of the SSA is much better than those of the ILS and the FSA. Furthermore, the SSA obtains better solutions in a much shorter time compared to the ACO. The SSA runs faster than the VNS and the solution quality of the SSA is still slightly better than that of the VNS.

5. Conclusions and future research directions

This paper proposes a simulated annealing heuristic for the TOPTW. Two versions of the proposed SA heuristic are developed

Table 8
Results for the test problems of Cordeau et al. ($m = 2$).

Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)	Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)
pro01	502	502.0	602.2	471	0.5	487.3	80.1	492	0.5	502	20.2	pro11	547	544.8	880.3	542	0.7	537.8	91.8	549	0.7	**566**	17.5
pro02	714	705.2	1017.6	660	1.2	696.9	216.0	686	1.2	712	37.3	pro12	768	763.4	2706.1	727	1.3	747.0	233.8	743	1.3	759	39.0
pro03	742	731.4	2083.0	714	3.3	715.3	356.0	710	3.3	741	217.7	pro13	831	798.8	3240.7	757	2.4	801.3	334.4	783	2.4	825	107.0
pro04	924	883.6	2439.3	863	4.1	906.4	578.5	889	4.1	905	245.0	pro14	1017	943.6	2100.7	925	8.1	990.6	725.0	861	8.1	922	111.7
pro05	1088	1021.8	2278.5	1011	7.1	1064.8	982.7	986	7.1	1053	249.8	pro15	1212	1100.0	3188.8	1126	8.2	1182.4	1019.1	1101	8.2	1155	444.8
pro06	1036	987.6	1724.1	997	9.8	1004.4	932.9	984	9.8	1022	439.3	pro16	1209	1101.0	2834.0	1110	11.0	1192.5	1192.0	1065	11.0	1094	330.7
pro07	566	566.0	972.3	552	1.0	550.1	130.0	559	1.0	566	20.5	pro17	652	646.2	1378.0	624	1.3	646.1	128.0	633	1.3	643	20.2
pro08	821	813.0	1730.0	796	5.1	799.6	344.7	793	5.1	**822**	75.6	pro18	938	888.4	1960.3	877	2.9	904.0	416.7	908	2.9	929	88.2
pro09	900	862.0	3131.0	867	5.2	855.7	608.5	847	5.2	854	120.7	pro19	995	940.8	2366.9	955	5.5	970.5	819.5	948	5.5	**1017**	302.7
pro10	1114	1064.6	2918.6	1004	10.3	1067.6	1018.9	1044	10.3	1069	313.2	pro20	1223	1113.0	3192.3	1056	10.7	1173.1	1227.6	1094	10.7	1154	554.5
Ave time			1889.7		4.8		524.8		4.8		173.9				2384.8		5.2		618.8		5.2		201.6
Ave RDP			2.74		5.40		3.05		4.52		1.61				5.09		6.80		2.55		6.65		2.77

Table 9
Results for the test problems of Cordeau et al. ($m = 3$).

Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)	Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)
pro01	619	619.0	117.0	598	0.4	613.5	79.2	606	0.4	614	18.7	pro11	654	649.0	237.3	632	0.5	649.6	58.5	645	0.5	654	12.8
pro02	942	938.4	2333.1	899	3.9	919.2	206.0	919	3.9	939	42.7	pro12	988	970.6	2883.7	902	1.8	982.2	194.8	921	1.8	967	43.0
pro03	1003	991.0	876.8	946	3.9	983.6	330.6	967	3.9	989	173.2	pro13	1111	1088.8	2515.5	1046	8.2	1081.3	309.5	1110	8.2	**1139**	80.3
pro04	1280	1226.4	2909.0	1195	9.0	1261.9	592.9	1185	9.0	1253	168.7	pro14	1343	1258.6	2084.7	1197	8.3	1318.7	549.8	1210	8.3	1289	166.3
pro05	1459	1386.6	2746.7	1356	12.5	1441.1	779.3	1392	12.5	1431	226.6	pro15	1619	1486.8	2671.8	1488	14.6	1597.1	885.0	1470	14.6	1550	414.2
pro06	1449	1359.0	2719.7	1376	19.2	1411.4	844.7	1343	19.2	**1469**	332.4	pro16	1635	1481.8	2284.5	1478	28.2	1615.8	1035.3	1445	28.2	1530	697.6
pro07	744	738.4	1330.6	713	1.0	730.2	136.1	717	1.0	742	24.9	pro17	830	821.0	832.0	808	0.9	824.3	114.5	765	0.9	**838**	38.0
pro08	1118	1115.0	2544.3	1082	4.3	1089.0	297.5	1081	4.3	**1131**	157.1	pro18	1242	1209.0	2854.3	1165	6.0	1220.4	326.3	1203	6.0	**1262**	164.1
pro09	1275	1210.0	3187.7	1144	10.3	1190.8	542.3	1163	10.3	1236	251.3	pro19	1378	1299.4	3094.8	1238	10.2	1339.1	630.9	1242	10.2	1329	220.7
pro10	1520	1457.2	2873.1	1473	27.9	1493.3	923.5	1423	27.9	1477	574.5	pro20	1682	1491.2	2823.0	1514	18.2	1640.2	1070.1	1545	18.2	1593	681.3
Ave time			2163.8		9.2		473.2		9.2		197.0				2228.2		9.7		517.5		9.7		251.8
Ave RDP			2.72		5.31		2.33		4.96		1.02				4.91		7.55		1.60		6.80		2.06

Table 10
Results for the test problems of Cordeau et al. ($m = 4$).

Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)	Name	BKS	ACO	T (s)	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)
pro01	657	655.2	15.4	644	0.2	656.4	50.1	649	0.2	657	15.5	pro11	657	657.0	0.1	654	0.2	657.0	28.0	654	0.2	657	13.5
pro02	1072	1067.8	2165.0	1014	2.4	1057.8	196.3	1051	2.4	1069	44.0	pro12	1132	1114.0	2486.7	1041	1.9	1117.6	143.7	1083	1.9	1116	134.2
pro03	1222	1204.6	2074.0	1162	10.5	1195.2	271.0	1194	10.5	1201	156.1	pro13	1329	1316.4	2926.3	1263	6.6	1302.6	250.6	1294	6.6	**1355**	112.6
pro04	1530	1506.0	2986.0	1452	11.6	1502.1	436.0	1540	11.6	**1535**	393.2	pro14	1625	1534.4	2730.2	1528	16.6	1612.9	423.5	1550	16.6	1586	192.5
pro05	1799	1722.2	2818.5	1665	19.6	1775.9	653.7	1672	19.6	1759	321.0	pro15	1958	1822.8	2631.3	1818	19.5	1934.0	690.0	1916	19.5	1929	518.6
pro06	1829	1723.5	2935.8	1696	35.4	1798.1	782.7	1704	35.4	**1839**	721.0	pro16	2016	1867.2	2614.7	1889	35.9	1968.9	824.5	1865	35.9	1921	769.7
pro07	872	865.4	1940.2	840	1.6	849.0	97.8	858	1.6	871	31.6	pro17	930	923.8	2749.7	889	1.9	924.7	78.9	914	1.9	926	30.5
pro08	1376	1351.6	2804.3	1267	6.9	1336.3	268.5	1337	6.9	1358	118.8	pro18	1510	1464.8	3209.1	1352	5.7	1485.5	255.1	1446	5.7	1455	104.8
pro09	1561	1554.2	3371.9	1460	13.8	1492.4	475.3	1468	13.8	**1565**	252.5	pro19	1695	1579.4	3293.9	1560	22.2	1659.8	523.3	1670	22.2	1695	277.6
pro10	1887	1819.8	3365.9	1782	38.7	1855.0	800.3	1777	38.7	1853	502.0	pro20	2008	1821.4	3193.0	1846	26.9	1988.3	862.4	1890	26.9	1901	685.8
Ave time			2447.7		14.1		403.2		14.1		255.6				2583.5		13.7		408.0		13.7		284.0
Ave RDP			2.02		5.57		2.00		3.49		0.63				4.22		6.38		1.28		3.50		1.75

Table 11
Results for the test problems of Cordeau et al. (new data set).

Name	m	OPT	ILS	T (s)	VNS	T (s)	FSA	T (s)	SSA	T (s)
pro01	3	657	608	0.7	612.9	69.6	611	0.7	614	18.5
pro02	6	1220	1180	4.5	1195.3	85.0	1192	4.5	1205	48.0
pro03	9	1788	1738	11.3	1759.0	86.0	1751	11.3	1758	124.2
pro04	12	2477	2428	45.4	2466.4	81.2	2444	45.4	2461	393.3
pro05	15	3351	3297	37.3	3349.5	71.7	3329	37.3	3351	1109.4
pro06	18	3671	3650	106.1	3670.1	83.5	3656	106.1	3661	1646.7
pro07	5	948	909	1.5	928.3	69.5	948	1.5	948	27.2
pro08	10	2006	1984	12.0	2005.0	63.2	2000	12.0	2006	128.5
pro09	15	2736	2729	33.0	2735.6	54.6	2731	33.0	2736	794.8
pro10	20	3850	3850	52.3	3850.0	52.4	3843	52.3	3847	1369.2
Ave time				30.4		71.7		30.4		566.0
Ave. RPD				2.32		1.30		1.44		1.04

Table 12
Average gaps for the ACO, ILS, VNS, FSA and SSA (%).

m	ACO					ILS					VNS					FSA					SSA				
	1	2	3	4	Var.*	1	2	3	4	Var.*	1	2	3	4	Var.*	1	2	3	4	Var.*	1	2	3	4	Var.*
Solomon 100	0.10	0.68	1.26	1.45	–	1.94	1.90	1.46	2.91	1.80	0.07	1.02	1.03	1.35	0.45	3.63	2.49	2.61	2.09	1.64	0.05	0.10	0.25	0.26	0.59
Solomon 200	1.88	2.84	0.80	0.02	–	2.69	2.75	1.71	0.00	0.39	0.71	0.65	0.09	0.00	–	3.16	2.75	0.99	0.00	0.40	0.66	0.61	0.43	0.00	0.08
Cordeau 1–10	1.20	2.74	2.42	2.02	–	4.72	5.40	5.31	5.57	2.32	1.08	3.05	2.33	2.00	1.30	5.26	4.52	4.96	3.49	1.44	0.97	1.61	1.02	0.63	1.04
Coredau 11–20	10.59	5.09	4.91	4.22		8.20	6.80	7.55	6.38		1.99	2.55	1.60	1.28		8.83	6.65	6.80	3.50		2.28	2.77	2.06	1.75	
Average	3.44	2.84	2.35	1.93	–	4.39	4.21	4.01	3.72	1.50	0.96	1.82	1.26	1.16	0.88	5.22	4.10	3.84	2.27	1.16	0.99	1.27	0.94	0.66	0.57

–: Solutions were not reported.
* Number of routes varies for instances in Solomon's and Cordeau et al.'s new data sets.

Table 13
Average CPU time for the ACO, ILS, VNS, FSA and SSA (seconds).

m	ACO					ILS					VNS					FSA					SSA				
	1	2	3	4	Var.*	1	2	3	4	Var.*	1	2	3	4	Var.*	1	2	3	4	Var.*	1	2	3	4	Var.*
Solomon 100	200.1	1278.6	1421.7	1523.0	–	0.2	0.9	1.5	2.4	3.2	85.4	68.8	68.9	66.8	20.9	0.2	0.9	1.5	2.4	3.2	22.3	34.5	45.9	58.3	90.7
Solomon 200	1193.4	2222.7	1345.0	245.4	–	1.7	2.6	1.7	1.0	1.5	857.8	813.7	322.3	141.2	–	1.7	2.6	1.7	1.0	1.5	44.7	79.6	52.2	40.4	48.4
Cordeau 1–10	1257.1	1889.7	2163.8	2447.7	–	1.8	4.8	9.2	14.1	30.4	822.1	524.8	473.2	403.2	71.7	1.8	4.8	9.2	14.1	30.4	112.2	173.9	197.0	255.6	566.0
Coredau 11–20	877.7	2384.8	2228.2	2583.5		2.0	5.2	9.7	13.7		832.9	618.8	517.5	408.0	–	2.0	5.2	9.7	13.7		162.4	201.6	251.8	284.0	
Average	882.1	1944.0	1789.7	1699.9	–	1.4	3.4	5.5	7.8	11.7	649.6	506.5	345.5	254.8	46.3	1.4	3.4	5.5	7.8	11.7	85.4	122.4	136.7	159.6	235.0

–: Solutions were not reported.
* Number of routes varies for instances in Solomon's and Cordeau et al.'s new data sets.

and compared with existing approaches for the TOPTW. Computational study indicates that both versions of the SA heuristic are capable of producing high quality TOPTW solutions. The fast version (FSA) is tailored for applications that need quick responses such as the personalized electronic tourist guide discussed in Vansteenwegen et al. (2009b). This approach solves the TOPTW fast and effectively. In fact, it finds many solutions that are equal to or better than the best-known solutions.

The SSA heuristic is suitable for applications in which solution quality is more important than the solution time. Computational study indicates that this approach outperforms the existing approaches. The SSA heuristic obtains best solutions for more than 1/2 of the benchmark instances for which the optimal solution is not known. Moreover, it finds 33 new best solutions. These new best solutions can be found at http://web.ntust.edu.tw/~vincent/op/. For benchmark problems with known optimal solutions, the solution obtained by the SSA is very close to the optimal solution. For the two Solomon's new data sets (c*/r*/rc*_100 and c*/r*/rc*_200) and the new data set converted from Cordeau et al.'s benchmark problems, the average gaps between the SSA solutions and the optimal solutions are merely 0.59%, 0.08% and 1.04% respectively.

The new best solutions obtained by the proposed SA heuristics may serve as benchmarks for future studies. The proposed approach may also be applied to other problems in a similar setting. As the TOPTW related problems are gaining more attentions from both the academic and the industry in recent years, it is quite possible that new variants of the problem will be proposed due to practical considerations. In that case, future research may also try to apply or modify the proposed SA approach to solve these variants.

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