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Near-optimal design of Global Positioning System (GPS) networks using the Tabu Search technique

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Abstract. This paper describes an optimization technique based on an heuristic procedure which is applied to analyse and improve the efficiency of the design of Global Positioning System (GPS) surveying networks. GPS is a valuable survey tool because of its ability to increase the accuracy, speed and flexibility of a survey. A GPS network can be defined as a number of stations, which are co-ordinated by a series of sessions, formed by placing receivers on stations. The goal is to select the best order in which these sessions can be organised to give the best possible schedule. Generally, solving large networks to optimality requires impractical computational time. This paper proposes a Tabu Search technique which provides optimal or near-optimal solutions for large networks with an acceptable amount of computational effort. Computational results for several case studies with known and unknown optimal schedules have been presented to assess the performance of the proposed technique.

Key words: Combinatorial optimisation problem (COP), Global positioning system (GPS), Heuristic, Tabu Search (TS)

1. Introduction

The Global Positioning System (GPS) (Figure 1) is a satellite-based radionavigation system developed and operated by the U.S. Department of Defense. However, it has also been available for civilian users since the beginning of the early 1980s. The GPS operational constellation consists of 24 satellites and permits land, sea, and airborne users to determine their three-dimensional position, velocity, and time. This can be achieved 24 h a day in all weather. GPS satellites continuously, under control of precise and stable frequency references, transmit radio signals to the earth while orbiting 20 000 km above the ground. The satellites use accurate atomic clocks and two frequency bands to transmit these signals that contain transmission time and information on the position of the satellites, etc. A receiver, with unknown position on the earth, deciphers the data and determines the transmission time of the signals. If the clock in the receiver is synchronized with the satellite clocks, measurements of the distance (or ‘range’) to three different satellites would

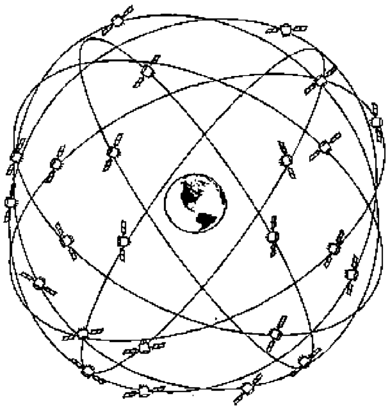


Figure 1. GPS satellite constellation (from Ref. [1]).

allow a user to compute a 3-D position. In practice, the range measurements contain a common bias due to non-synchronization of the receiver clock with the satellite clock. This bias is an additional unknown and the measurement of range from a fourth satellite is needed for determining accurate positions as shown in Figure 2. The quality of a location estimate depends upon many factors: for example, the number of satellites in view and their distribution relative to the receiver, errors in the predicted ephemeris of the satellites, unmodelled ionospheric and tropospheric propagation delays, interference from local reflections, and receiver noise [2,3].

Sequencing and scheduling play a crucial role in GPS fieldwork management, and capacity management is now a major focus to obtain a competitive advantage. In the current competitive economic environment, the efficient scheduling of GPS fieldwork has become an important necessity. GPS fieldwork consists of controllable and uncontrollable variables such as time, cost, personnel, location of stations, sessions to be observed and the movement of receivers. Using the GPS technique is highly expensive and cost becomes crucial on large projects. Surveyors have to meet committed observing times and schedules to use the receivers in the most efficient manner. To maximise the benefit of using this system, the Tabu Search (TS) heuristic technique has been researched, designed, implemented and analysed in relation to determining an efficient schedule. The rest of this paper is organized as follows. A general framework is described for GPS surveying network design focussing on the session scheduling problem as a Combinatorial Optimisation Problem (COP). Then, the search strategy of the TS technique, its structural elements and tabu parameters are explained and followed by a general procedure for the TS technique applied to GPS surveying. Subsequently, the general case of the problem is addressed by presenting several case studies for known and unknown optimal schedules and the obtained numerical results are reported. A summary of the conclusions follows and the paper ends with a discussion of possible directions for future research.

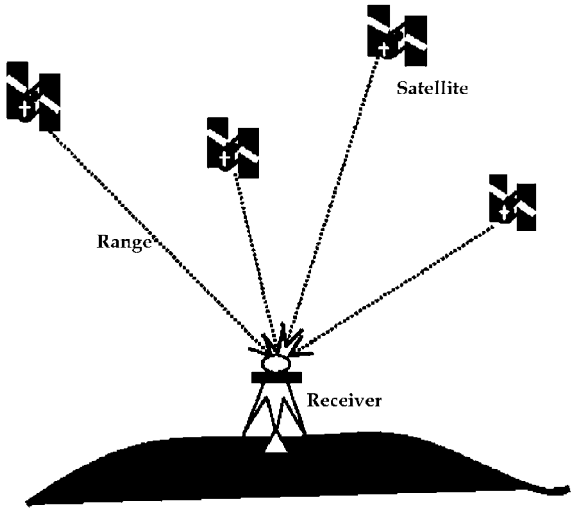


Figure 2. The 3-D Position from four satellites.

2. Preparing the GPS Surveying Network Problem for Combinatorial Solution

The process of designing a GPS surveying network can be described as follows. A number of receivers (at least two) are placed at stations and take simultaneous measurements from satellites. Each receiver can observe at most one station at a time. The receivers (X, Y, Z, etc.) are then moved to other stations (a, b, c, d, e, f, etc.) for further measurements as shown in Figure 3. The purpose is to obtain highly accurate measurements which define the three-dimensional positions of the receivers relative to each other. These positions can be used in a vector (distance *ab, bc*) determination between receivers as shown in Figure 3. Each session uses a certain number of receivers to simultaneously record satellite signals for a fixed duration. The problem is to search for the best order in which these sessions can be organised to give the best (minimal cost) schedule to complete all sessions.

Given a required measure of precision and reliability, the number of receivers r and the location of the network stations n, one of the challenges is to determine which stations are to be occupied at each session. For cost control, given the sessions to be observed u, and given the cost to move GPS receivers between stations C_{ij}, the challenge is to determine the order of the sessions (the session schedule) that gives the minimum cost. If V represents a schedule consisting of the required sessions u, then the number of possible schedules $u!$ is clearly very large. Exact methods can solve only small networks and are not practical as the size of the network increases [4]. Therefore, the need for an effective scheduling procedure in GPS surveying is necessary. The aim is to determine an optimal solution or close to it that minimises the total cost of observing the whole network and satisfies the requirements of GPS surveying, i.e.,

$$\text{Minimize} \sum_{q \in R} C(S_q)$$

$$\text{subject to:} \bigcup_{q \in R} S_q \supseteq N$$

where

S_q: the route of the receiver q in a schedule;

$\sum C(S_q)$: the total cost of carrying out the survey of the whole network using all the receivers;

N: the set of stations $N=\{1,...,n\}$;

R: the set of receivers $R=\{1,...,r\}$;

U: the set of sessions $U=\{1,...,u\}$.

3. The Tabu Search (TS) strategy

The TS technique is derived from work by Glover [5,6] with ideas and contributions from other works [7,8]. The success of the TS technique applied to COPs is seen by the improved solutions to problems in scheduling and sequencing. Such problems may include flow shop scheduling [9–12] and machine scheduling [13] as well as resource location and allocation such as the quadratic assignment problem [14–16]. In this section, a TS procedure for GPS network design is outlined. Its structural elements and control parameters are defined in subsequent sub-sections, while results of computational tests are discussed in Section 4.

3.1. STRUCTURAL ELEMENTS

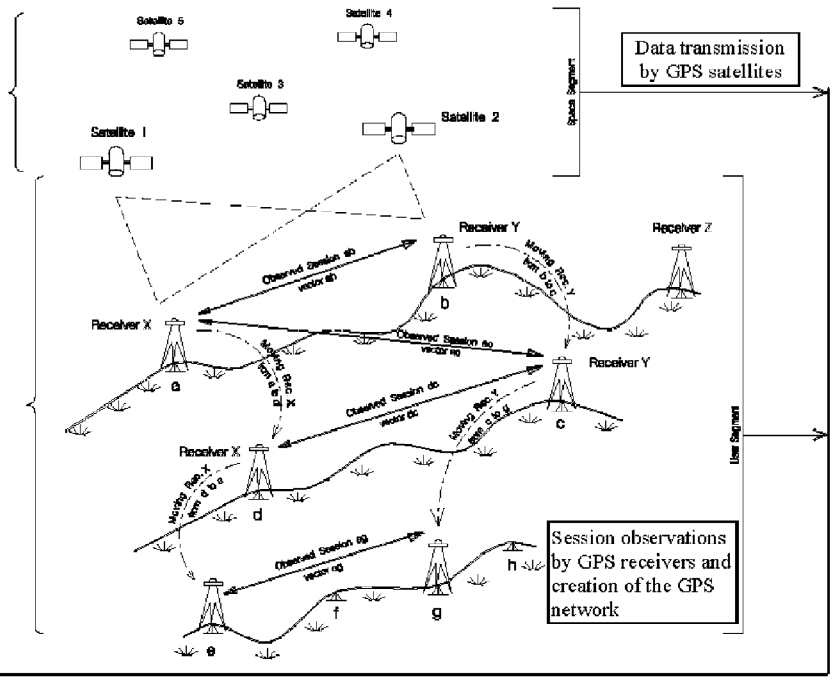
The structural elements determine the way in which a GPS network is modelled in order to fit into the TS framework. They involve the following:

3.1.1. *The initial schedule*

The initial schedule for a GPS network problem can be created by any feasible random or constructive procedure. For example, the initial schedule V_0 in Table 1 was randomly selected for the network in Figure 6.

3.1.2. *Neighbourhood structure*

The effectiveness of any iterative technique is partly determined by the efficiency of the mechanism by which neighbouring schedules are generated and the way in which a neighbourhood is searched for a better schedule [17]. In GPS scheduling,



No.	Session	Receiver X at:		Receiver Y at:		Receiver Z			Session Cost
		Station	Moving Cost	Station	Moving Cost				
1	ab	a	[- -]	b	[- -]				- -
2	ac	a	[0]	c	[C_{bc}]				C_{bc}
3	dc	d	[C_{ad}]	c	[0]				C_{ad}
4	eg	e	[C_{de}]	g	[C_{eg}]				$C_{de} + C_{eg}$
The Total Cost of the Schedule									ΣC_{ij}

Figure 3. Sessions observation using GPS receivers.

the neighbourhood structure I(V) is created by moves (interchanges) of the adjacent sessions in the initial schedule using the sequential search structure. This search structure examines the session-interchanges in the order (1, 2), (1, 3), (1, 4), ...,

Table 1. The initial schedule V_0 for two receivers (from Ref. [19]).

Session	Receiver 1at station	Receiver 2 at station
u_{ab}	a	b
u_{ac}	a	c
u_{ad}	a	d
u_{cb}	c	b
u_{cd}	c	d
u_{bd}	b	b

$(1, u)$, $(2, 3)$, $(2, 4)$, $(u - 1, u)$, etc. The size of the neighbourhood depends on the number of sessions in the initial schedule and it can become prohibitively large.

3.1.3. *The best move selection strategy*

The function of the move is to transform a schedule into a better schedule in its neighbourhood. The potential move selection strategy assumes that moves with a better value have a higher probability of reaching the best schedule or achieving a good schedule. This strategy of selection of a potential move as proposed by Glover and Laguna [18] is modified and adopted. In this paper, this strategy selects the greatest improvement or the smallest lack of improvement in the cost function, subject to the aspiration criterion and tabu restriction being satisfied.

3.1.4. *Attribute-based memory*

In the TS technique, an attribute of a move from one schedule to another is any aspect that changes as a result of this move. More than one type of move attribute can be operated in this technique, for example, general attribute types such as increasing or decreasing the value of the cost function, and specific attribute types such as swapping two sessions in a feasible schedule. In general, a move is effectively represented by its ordered pairs of attributes (From-Attribute, To-Attribute). For example as shown in Figure 3, this single move from session u_{ab} to session u_{dc} has many attributes and can be represented by *from* or *to* attributes. In such pairs, *From-Attributes* are associated with the previous schedule *V* (i.e., before a swap between u_{ab} and u_{dc}), whereas *To-Attributes* are associated with an obtained new schedule V’ (i.e., after a swap between u_{ab} and u_{dc}). Any move containing tabu attributes is not available for subsequent selection as a neighbourhood candidate (unless certain aspiration criteria are first satisfied).

The most common tabu restrictions are designed to prevent the search from reversing or repeating itself (cycling). For example, consider the GPS network as shown in Figure 6 in which a schedule to this network consists of a random permutation of the observed sessions. If the previous move consisted of swapping the session u_{ab} to session u_{ac} then the values involved in this swapping procedure can be used as a potential move attribute and can be classified as tabu. This means that in the subsequent iterations of the TS procedure these two sessions are not allowed to be swapped since the associated move attributes are tabu. However, the tabu status of a move attribute can be overridden in certain cases. In other words, if the aspiration criteria are met then the move can be processed as if it were not tabu.

3.1.5. *Aspiration criteria*

In certain circumstances when adopting the TS technique, active tabu restrictions can be overruled if certain ‘aspiration criteria’ are met. These criteria are measures purposely designed to override the tabu status of a move in case this move is good and sufficient to prevent cycling. In the developed technique, a standard implementation of aspiration levels is adopted. These levels allow tabu restrictions to be overridden if the potential move produces a schedule better than the best schedule found so far. For more details about other aspiration levels the reader should refer to Glover and Laguna [18].

3.2. TABU PARAMETERS

These parameters govern the workings of the TS technique itself and depend mainly on the size and type of the network. Figure 4 illustrates the tabu parameters which can be summarized as follows:

3.2.1. *Tabu List (TL)*

The TL parameter is a memory structure which, to avoid ‘cycling’, prohibits moves that have recently been swapped. Cycling in the TS technique is eleminated because a move that has just been used becoming immediately used in the opposite sense. To prevent this, the move becomes prohibited and is inserted in an updated matrix structure $[u \times u]$ called a tabu list. The size of this list is a function of the number of observed sessions u. The TL parameter contains a short-term memory for the very recent history and long-term memory for the distant history. At the beginning of the process, a ‘wide explore’ for the search process is applied to identify good and bad regions; this process in TS is called *intensification* (recency). When a good schedule is obtained, the search is exploited to generate the best possible schedule in this good area; this process in TS is called *diversification* (frequency).

3.2.2. *Candidate List (CL)*

The main objective of the CL parameter is to decrease the computational effort for the entire neighbourhood. This can be achieved by considering only a favourable subset of all the moves that are available for the current schedule. This subset of

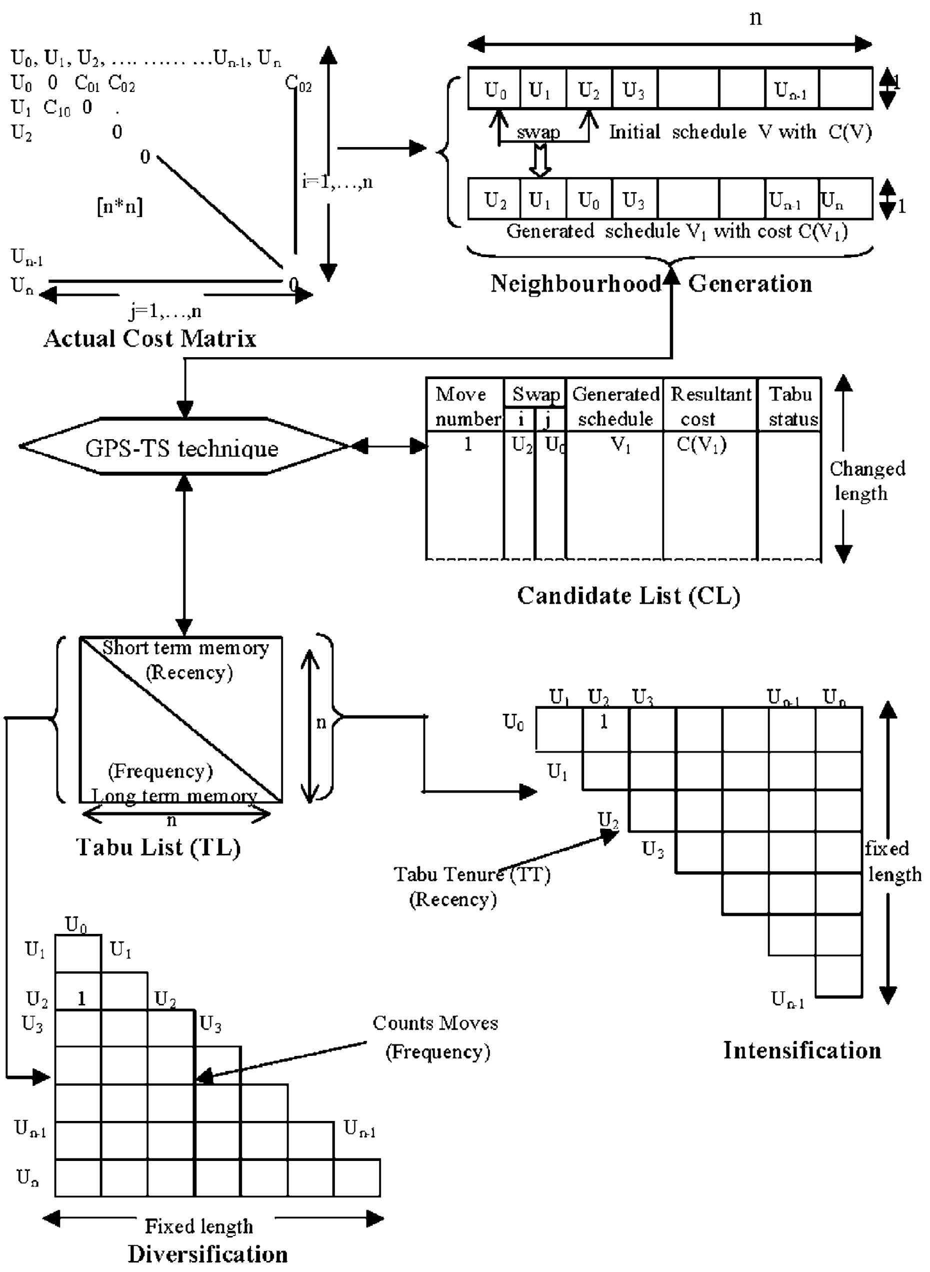


Figure 4. The TS components.

moves is most likely to lead to a better schedule. The preferred attribute of the CL parameter is adopted which contains the potential set of moves that give the best neighbouring schedules surrounding the current schedule. In general, for each iteration the number of possible moves on the CL parameter varies according to its length. In this paper, a fixed length of the CL parameter is adopted which suits the static nature of a GPS network and can be determined by the user.

3.2.3. *Tabu Tenure (TT)*

The TT parameter implements a strategy known as dynamic updating of the tabu time. This parameter is initialised to a given value of the *start-tenure* and is modified according to the evolution of the search. If its value is too small, cycling may occur in the search process. By contrast, if its value is too large interesting swaps may be prohibited. This latter result would lead to the exploration of lower quality schedules and produce a larger number of iterations to obtain the best possible schedule. However, it is difficult to give a general rule for determining the best value for this parameter.

3.2.4. *The stopping criteria (KK)*

The TS technique may adopt various stopping criteria. The simplest one, which has been adopted here, is to stop after a pre-defined number of iterations. The number of performed iterations represents the total processing time of the TS technique to obtain the best possible schedule. Each iteration of the tabu process requires four steps. First, the search process has to be perturbed to generate the CL parameter for the current schedule. Second, the tabu status of the best potential move in the CL parameter has to be checked to produce the best found schedule. Third, if necessary the current schedule is replaced by the best found schedule. Fourth, the TL parameter is updated by storing the attributes of the best found schedule in it and using them in the subsequent iterations.

3.3. THE TS PROCEDURE

In this section, the design of the TS technique is explained and the detailed step-by-step procedure is outlined in Figure 5. Having chosen the initial schedule and its neighbourhood structure, the move is defined. Then, the TS technique starts with an empty TL parameter, i.e., it is filled with zeros, indicating no moves are classified tabu at the beginning of the search. At each iteration, all possible moves are evaluated and the best are selected by the CL parameter. Then, the move which potentially gives the best found schedule is investigated. The best-found schedule and associated tabu parameters are continuously updated. The TL parameter does not permit the search to turn back to schedules visited in previous iterations by storing their attributes (moves) as tabu. However, it may happen that an interesting move is tabu. Therefore, an aspiration function must be defined in order to evaluate the advantage of using this prohibited move again.

By applying the acceptance strategy, the best potential move is selected to produce the highest evaluation in terms of cost and tabu restrictions. If this evaluation

```
[I]   INITIALISATION:
      (A) FORMULATING the original cost matrix:
  {Original cost matrix represents the cost of moving the receiver from one station to another}
                Insert the total number of stations, n.
                Insert the estimated cost for each receiver's move.
      (B) CREATING the actual cost matrix:
  {Actual cost matrix represents the cost of moving the receiver from one session to another}
                Insert the number of receivers, r.
                Define the sessions to be observed, u.
      (C) DETERMINING an initial schedule:
                Create a feasible schedule V with cost C(V).
      (D) INITIALIZING the tabu parameters:
                Set the Tabu List, TL(uxu);
                Set the Candidate Length, CL;
                Set the Tabu Tenure, TT;
                Set the iteration counter, KK=0.
[II]  SELECTION AND ACCEPTANCE STRATEGY
      (E) SELECTING the best admissible move of cost $C(V_{best})$:
                Create neighbours I of $V_{int}$;
                Construct a CL for $V_{int}$ using I;
                Improve $V_{int}$ into $V_{best}$ with $C(V_{best})$.
      (F) UPDATING the tabu parameters:
                Build up the TL by adding TL=[ $C(V_{best})$ ,..];
                $V_{best}$ becomes the best possible new schedule;
                Update the counter KK=KK+1, and the process continues.
[III] THE STOPPING RULES:
      (G) TERMINATING the search:
                Stop if the stopping criterion is satisfied;
                    Given number of iterations, OR
                    Maximum number of iterations allowed without improving
                        the best obtained schedule.
                OTHERWISE.
                    Go to (E).
      (H) DECLARING the output:
                Declare the best obtained schedule;
                Declare the computation time;
              END.
```

Figure 5. The general outline for the TS procedure.

is acceptable, then the tabu status of the prohibited move is dropped and the move can be performed. If the best move is not accepted, the next best move in the CL parameter is considered, and so on. Because the capacity of the TL parameter is limited, it is necessary to determine how long a move remains on this list and this is known as tabu tenure. The stopping criterion is met when the number of iterations (KK), for which there is no improvement over the best found schedule, is greater than a constant value which is fixed *a priori*. To successfully implement the TS technique, the tabu status must be maintained. If a tabu move would give

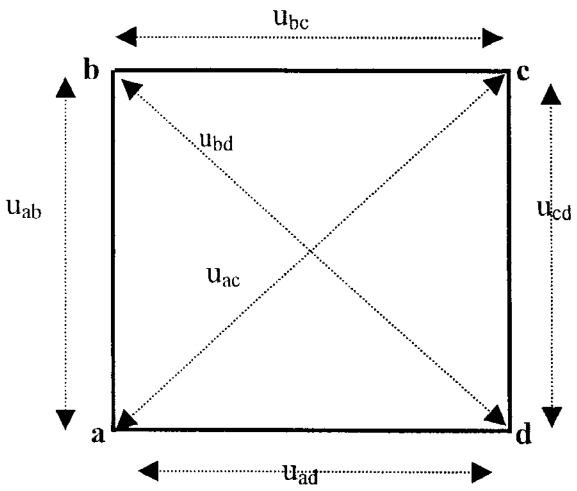


Figure 6. Simple four station network (from Ref. [19]).

a schedule better than any visited so far, its tabu status may be overridden. The aspiration criterion represents the condition that allows such an override to occur. Other advanced and more sophisticated elements of the TS technique are discussed in Glover and Laguna [18].

4. Testing the TS Performance

This section reports on the computational experience of the TS technique using GPS networks with known and unknown optimal solutions. The performance of the TS technique was evaluated with respect to the schedule quality and computational effort. The computational procedure is shown in detail in the following sections.

4.1. KNOWN SOLUTIONS

The best known solutions were obtained for relatively small GPS surveying networks using the Travelling Salesman Problem (TSP) algorithm. The optimal operating schedules for two case studies were based upon a Branch-and-Bound (BB) method and obtained from Dare [19]. The first case, which is a hypothetical network, as shown in Figure 6, has an optimal schedule with a cost of 13 units. The data set for this hypothetical network consists of four stations (n=4), two receivers (r=2) and six sessions (u=6). The initial starting schedule V_0 with a cost of 17 units was randomly chosen and consisted of the following sessions u_{ab}, u_{ac}, u_{ad}, u_{bd}, u_{cd}, $u_{cb,}$ as shown in Table 1.

In the beginning, the value of the TT parameter is set to 3 (TT=3), i.e., the current move for the first iteration is kept as a prohibited move for three successive iterations. Also, the TL parameter is initially empty, i.e., it is filled with zeros, indicating no moves are classified tabu at the beginning of the search, as shown in Figure 7A. The size of the TL parameter is [6×6] according to the number of sessions in the initial starting schedule (*u*=6). A suitable evaluation neighbourhood is designed to provide all the possible move values for this network as shown in Figure 7B. After generating the neighbourhood, the length of the CL parameter is fixed (CL=4) by selecting the best four moves in the generated neighbourhood as shown in Figure 7C.

Basically, it is not necessary for the CL parameter to sort and identify each of the four best moves, since it is the best move, which leads to the cheapest schedule, that is interesting. The additional options are included in the CL parameter to clarify the concept of the *TS* strategy subsequently presented. The top schedule in the CL parameter (*M*=0 with entry *i*=0 and *j*=1), which represents a local maximum for the initial schedule, results from swapping the sessions ($i = u_{a-b}$) and ($j = u_{a-c}$). Hence, this local maximum of the initial schedule (V_0) represents the new current schedule (V_1) for the next iteration. The aim from this illustration is to show the important function of the selection and accepting strategy of the TS technique. The CL parameter in each iteration selects the best four schedules and arranges them in descending order. Then, the TS technique selects the best schedule, which is not tabu, and makes this the current schedule which is to be used in the next iteration.

The new current schedule V_1 = (u_{ac} u_{ab} u_{ad} u_{bd} u_{cd} u_{cb}) has a cost value of 13 units. Figure 8A now shows that swapping the positions of sessions u_{ab} and u_{ac} is forbidden for three iterations (TT =3). TT=3 is located in the upper diagonal recency-based memory of the TL with entry ($i = 0$, $j = 1$). The lower diagonal of the TL contains the frequency counts for the move in this iteration. This frequency-based memory provides information that complements the information provided by recency-based memory to broaden the scope for the selection strategy for the best move. The effect and action of this strategy is complementary between both memories and will be seen through the following iterations. The neighbourhood for V_1 is generated and the new CL parameter is formulated for the second iteration. The most improving move at this step is the second one in the CL, as shown in Figure 8B. This move ($M = 5$ with entry $i = 1$, $j = 2$) creates the best schedule and represents the local maximum of V_1 because the first move ($M = 0$ with entry $i = 0$, $j = 1$), which has the same cost as the second one, is forbidden for the 3 successive iterations (TT=3). Hence, no cycling will occur. The local maximum of V_1 represents the new current schedule for the next iteration which is V_2= (u_{ab} u_{ad} u_{ac} u_{bd} u_{cd} u_{cb}).

The new current schedule V_2 becomes the best schedule found so far and has a cost value of 13 units. At this iteration, the interchange of one pair of previous sessions is classified tabu, as indicated by non-zero entries in the upper diagonal recency-based memory of TL in Figure 9A. As is noticeable, the swapping of sessions u_{ab} and u_{ac} ($M = 0$ and entry $i = 0$, $j = 1$ in Figure 7B) has decreased the TT value from three to two remaining iterations (TT=2), while the swapping of the sessions u_{ac} and u_{ad} ($M = 5$ and entry $i = 1$, $j = 2$ in Figure 8B) is forbidden for u=6

u=6

= 0 0 0 0 0
0 = 0 0 0 0
0 0 = 0 0 0
0 0 0 = 0 0
0 0 0 0 = 0
0 0 0 0 0 =

(A) Tabu List [uxu].

Move number M	Swap u_i u_j	Generated schedules V	Resultant cost C(V)
0	i=0 j=1	u_{ac} u_{ab} u_{ad} u_{bd} u_{cd} u_{cb}	13
1	i=0 j=2	u_{ad} u_{ac} u_{ab} u_{bd} u_{cd} u_{cb}	14
2	i=0 j=3	u_{bd} u_{ac} u_{ad} u_{ab} u_{cd} u_{cb}	15
3	i=0 j=4	u_{cd} u_{ac} u_{ad} u_{bd} u_{ab} u_{cb}	24
4	i=0 j=5	u_{cb} u_{ac} u_{ad} u_{bd} u_{cd} u_{ab}	24
5	i=1 j=2	u_{ab} u_{ad} u_{ac} u_{bd} u_{cd} u_{cb}	13
6	i=1 j=3	u_{ab} u_{bd} u_{ad} u_{ac} u_{cd} u_{cb}	18
7	i=1 j=4	u_{ab} U_{cd} u_{ad} u_{bd} u_{ac} u_{cb}	27
8	i=1 j=5	u_{ab} u_{cb} u_{ad} u_{bd} u_{cd} u_{ac}	27
9	i=2 j=3	u_{ab} u_{ac} u_{bd} u_{ad} u_{cd} u_{cb}	20
10	i=2 j=4	u_{ab} u_{ac} u_{cd} u_{bd} u_{ad} u_{cb}	22
11	i=2 j=5	u_{ab} u_{ac} u_{cb} u_{bd} u_{cd} u_{ad}	22
12	i=3 j=4	u_{ab} u_{ac} u_{ad} u_{cd} u_{bd} u_{cb}	19
13	i=3 j=5	u_{ab} u_{ac} u_{ad} u_{cb} u_{cd} u_{bd}	16
14	i=4 j=5	u_{ab} u_{ac} u_{ad} u_{bd} u_{cb} u_{cd}	17

(B) Neighbourhood of V_0.

Move number M	Swap u_i u_j	Generated schedules V	Resultant cost C(V)	Tabu status
0	i=0 j=1	u_{ac} u_{ab} u_{ad} u_{bd} u_{cd} u_{cb}	13	Best
5	i=1 j=2	u_{ab} u_{ad} u_{ac} u_{bd} u_{cd} u_{cb}	13	
1	i=0 j=2	u_{ad} u_{ac} u_{ab} u_{bd} u_{cd} u_{cb}	14	
2	i=0 j=3	u_{bd} u_{ac} u_{ad} u_{ab} u_{cd} u_{cb}	15	

CL=4

(C) Candidate List (CL=4).

Figure 7. The tabu parameters for iteration 0.

three iterations (TT =3). The lower diagonal frequency-based memory of the TL now contains the frequency counts of both the previous moves. The neighbourhood for V_2 is generated and the new CL parameter is formulated for the third iteration, as shown in Figure 9B. The top schedule ($M = 13$ with entry $i = 3$, $j = 5$) in the CL parameter represents the local maximum of V_2 which will be used as a

=	3	0	0	0	0
1	=	0	0	0	0
0	0	=	0	0	0
0	0	0	=	0	0
0	0	0	0	=	0
0	0	0	0	0	=

(A) Tabu List.

Move number M	Swap u_i u_j	Generated schedules V	Resultant cost C(V)	Tabu status
0	i=0 j=1	u_{ac} u_{ab} u_{ad} u_{bd} u_{cd} u_{cb}	13	Tabu
5	i=1 j=2	u_{ab} u_{ad} u_{ac} u_{bd} u_{cd} u_{cb}	13	Best
1	i=0 j=2	u_{ad} u_{ac} u_{ab} u_{bd} u_{cd} u_{cb}	14	
2	i=0 j=3	u_{bd} u_{ac} u_{ad} u_{ab} u_{cd} u_{cb}	15	

(B) Candidate List.

Figure 8. The tabu parameters for iteration 1.

=	2	0	0	0	0
1	=	3	0	0	0
0	1	=	0	0	0
0	0	0	=	0	0
0	0	0	0	=	0
0	0	0	0	0	=

(A)Tabu List.

Move number M	Swap u_i u_j	Generated schedules V	Resultant cost C(V)	Tabu status
13	i=3 j=5	u_{ab} u_{ad} u_{ac} u_{cb} u_{cd} u_{bd}	13	Best
14	i=4 j=5	u_{ab} u_{ad} u_{ac} u_{bd} u_{cb} u_{cd}	13	
1	i=0 j=2	u_{ac} u_{ad} u_{ab} u_{bd} u_{cd} u_{cb}	14	
0	i=0 j=1	u_{ad} u_{ab} u_{ac} u_{bd} u_{cd} u_{cb}	15	

(B) Candidate List.

Figure 9. The tabu parameters for iteration 2.

current schedule for the next iteration. The above process of the TS strategy to find the best schedule continues till the final iteration. To illustrate the power of the TS

=	0	1	0	0	0
1	=	2	0	0	0
1	2	=	0	0	0
0	0	0	=	3	0
0	0	0	2	=	0
0	0	0	1	0	=

(A) Tabu List.

Move number M	Swap u_i u_j	Generated schedules V	Resultant cost C(V)	Tabu status
6	i=3 j=4	u_{ac} u_{ab} u_{ad} u_{cb} u_{cd} u_{bd}	13	Bset
13	i=1 j=2	u_{ac} u_{ad} u_{ab} u_{cd} u_{cb} u_{bd}	13	
14	i=3 j=5	u_{ac} u_{ab} u_{ad} u_{bd} u_{cb} u_{cd}	13	
2	i=0 j=1	u_{ad} u_{ab} u_{ac} u_{cd} u_{cb} u_{bd}	14	

(B) Candidate List.

Figure 10. The tabu parameters for iteration 8.

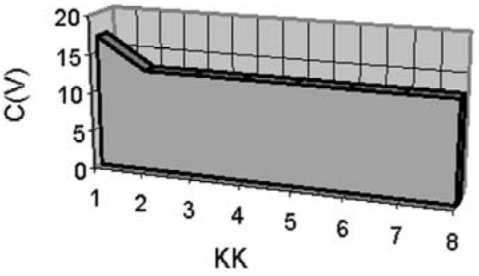


Figure 11. Th graph of V_{BFS} versus number of iterations KK for TS applied to network in Figure 6.

memory, assume that seven iterations have been performed so that we now move to iteration 8.

At this iteration, another cheapest schedule V_8 is found with the best cost of 13 units. The recency-based memory in Figure 10A indicates that the last three session pairs swapped were; sessions u_{ab}, u_{ad} with entry ($i = 0, j = 2$), sessions u_{ac}, u_{ad} with entry ($i = 1, j = 2$) and sessions u_{bd}, u_{cd} with entry ($i = 3, j = 4$). The frequency-based memory counts show the distribution of moves throughout the first seven iterations. The function of these counts is to diversify the search and redirect it into new regions. A residence frequency indicates that a move is highly attractive and will give a high quality schedule, or it may indicate the opposite! A surveyor can find out from the counts of 2 in the lower diagonal of Figure 10A that the swap between session u_{ad} and $u_{ac}$is highly attractive and will give good

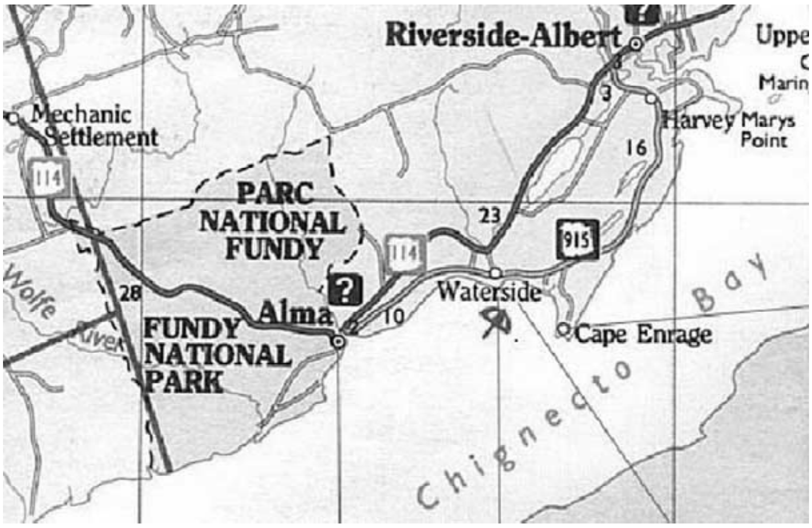


Figure 12. Fundy Park, Canada.

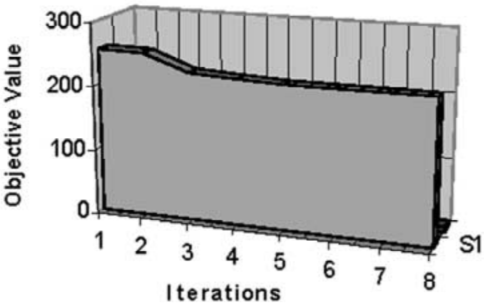


Figure 13. Graph of the objective function value versus iteration number for the TS heuristic applied to the Fundy Park network.

reduction in the cost of the schedule. On the other hand, a count of 0 for example, indicates the swap between u_{bd} and u_{ad} is inefficient and will give a low quality schedule.

The process of the TS technique is terminated when the stopping criterion is met. The adopted stopping criterion was to stop after a defined number of iterations, KK=8. The schedule obtained using the TS technique had a cost of 13 units (the same cost as the known optimal schedule) [20]. Figure 10 shows the performed tabu list and the candidate list, while Figure 11 shows a graphical depiction of the fast convergence of the TS heuristic for this network.

The second case study within the group of known solutions represents an actual GPS network as shown in Figure 12. This real network consists of six stations ($n = 6$), two receivers ($r = 2$) and ten sessions ($u = 10$). By applying the TS technique, the same cost as the optimal schedule was obtained [21]. Figure 13

```
Recency based memory
= 3 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2 = 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1 0 = 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1 0 0 = 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 = 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 = 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 = 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 = 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 = 1 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 1 = 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 = 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 = 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 = 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 = 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 = 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 = 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 = 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 = 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 = 0
0 0 0 0 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 =
Frequency based memory
```

Figure 14. The Tabu list size [20×20] for the Fundy Park network.

depicts the cost changes of the initial schedule as the TS technique proceeds and stops where there is no further improvement. The selected tabu parameters are: CL= 5, TT= 3, KK= 8, and TL=[19×19], as shown in Figure 14.

4.2. UNKNOWN SOLUTIONS

To generalise the above developed procedure, the tabu parameters have been fully investigated using real networks of different types and sizes – with larger networks more meaningful analysis can be carried out. The goal of the investigation is to control the behaviour of the developed technique by the variation of the tabu parameters. The Relative Reduction of the Cost (RRC) measure will be used to evaluate the effect of these parameters on the computational effort and the quality of the best-found schedule V_{BFS}, i.e.,

$$\mathrm{RRC} = [(C_{\mathrm{INT}} - C_{\mathrm{BFS}})/C_{\mathrm{INT}}] \times 100$$

where C_{INT} = the Cost of the Initial Schedule V_{INT}; C_{BFS} = the Cost of the Best Found Schedule V_{BFS} by the TS technique.

The first network, which is a triangular-type GPS network for Malta, consists of 25 stations as shown in Figure 15. The initial schedule with a cost of 1405 min was composed of 38 sessions observed using two and three receivers [22]. Using the TS technique, the overall cost of the initial schedule was reduced to 1080 min after 40 iterations as shown in Figure 16. The data structure of the TL parameter, which was constructed and updated circularly after each iteration, is shown in Figure 17 with a size of [38×38]. The other selected parameters are CL=10, TT=3 and KK=40

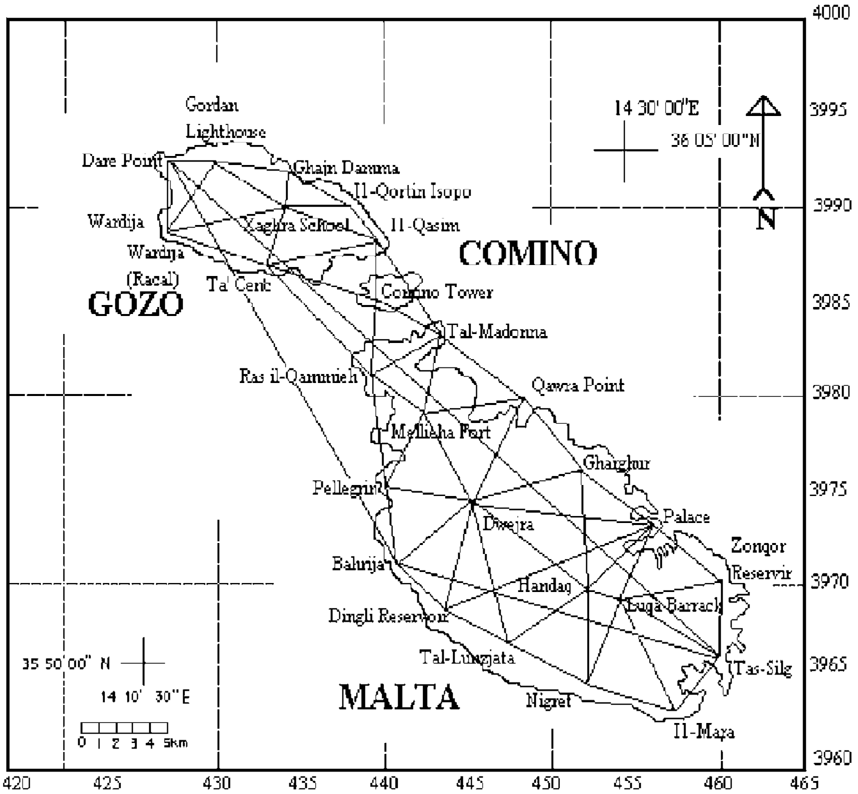


Figure 15. Malta GPS survey network (from Ref. [19]).

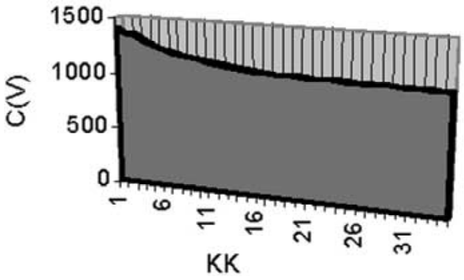
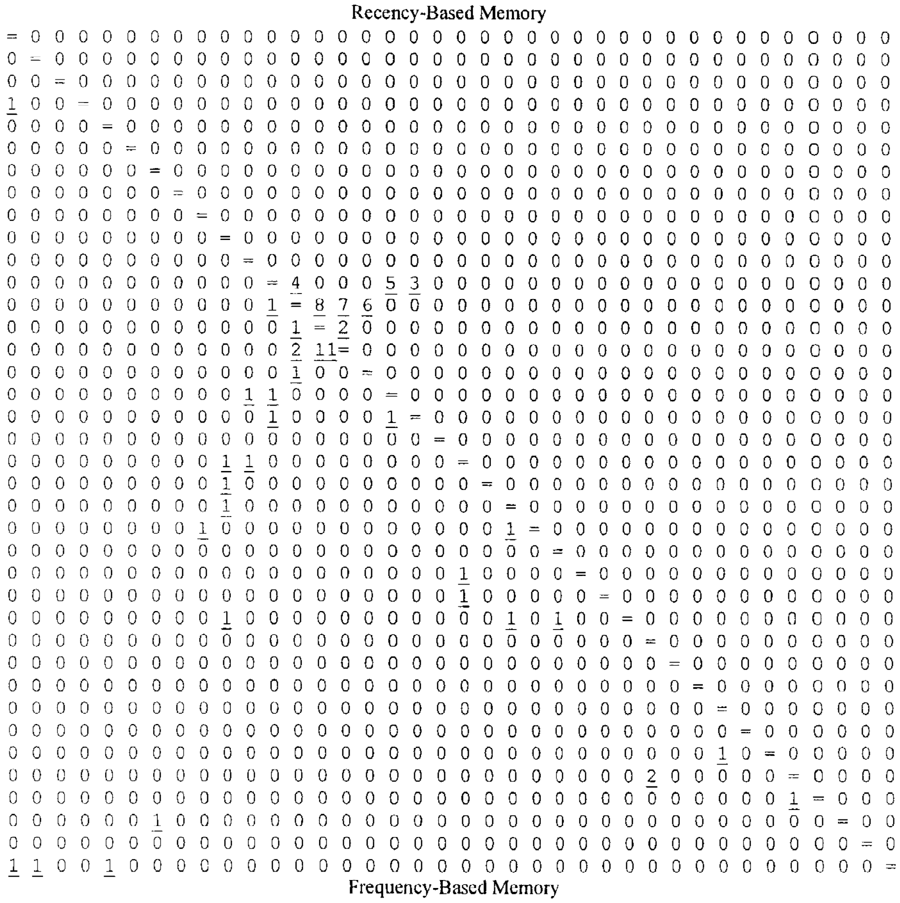


Figure 16. The graph of V_{BFS} versus number of iterations KK for the TS technique applied to the Malta GPS network.

iterations [23].

For the investigation of the behaviour of the TS technique as a function of the CL parameter, the values of both TT and KK parameters are fixed. Increasing the value of the CL parameter from 5 to 14, the quality of the obtained schedules does not seem to be affected at all, as shown in Figure 18. The main reason for this



Recency-Based Memory

=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	=	4	0	0	0	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	=	8	7	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	=	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	2	11	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	=	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	=	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	=	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	=	0	0	0
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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0
1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=

Frequency-Based Memory

Figure 17. The tabu list structure [38×38] for the Malta network.

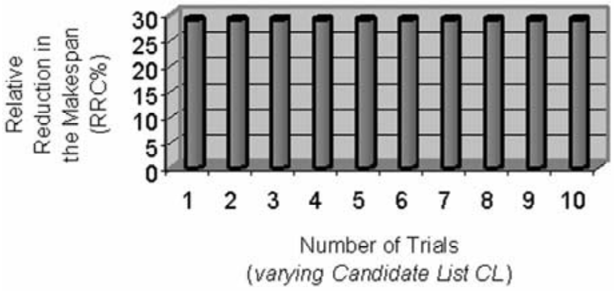

Figure 18. The computational result for varying CL and keeping fixed TT and KK.

behaviour seems to be the efficiency of the CL strategy. This strategy, for every tabu configuration search, discards most of the admissible moves and keeps only those leading to good schedules.

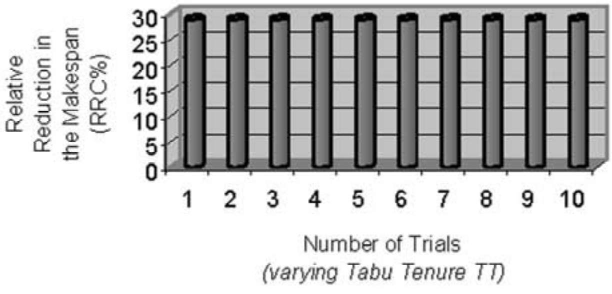

Figure 19. The computational results for varying TT and keeping fixed CL and KK.

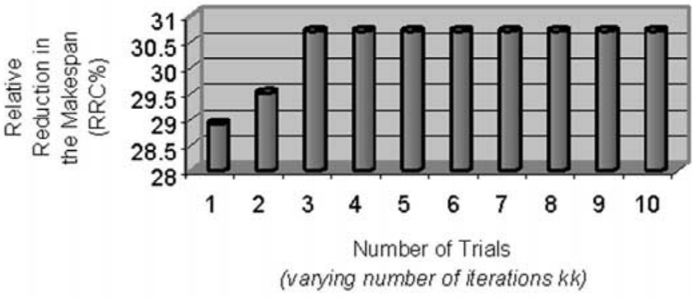

Figure 20. The RRM versus the number of trials for a varying KK.

The quality of the obtained schedules does not seem to be affected at all by fixing both the CL and KK parameters and increasing values of the TT parameter from 3 to 12. These experimental observations show that the cycling phenomenon does not always appear with a small TT value, as shown in Figure 19. The intuitive justification for this result is the fact that smaller TT values enable more careful examination of the cost space (provided that no cycling occurs): this phenomenon is in agreement with other work [8].

Figure 20 shows the behaviour of the RRC obtained through the use of the TS technique, with respect to the variation of the KK parameter and fixed CL and TT parameters. Values of RRC ranging from 22.42 to 23.49% were observed as the KK parameter increased from 20 to 65 iterations, but the RRC then remained fixed.

In previous investigations, the effect of tabu parameters were evaluated individually until no further improvement can be achieved. In some cases, it may happen that a gain in the performance of the TS technique can be obtained by simultaneously changing the values of these parameters. The goal is to stimulate the finding of other high quality schedules by combining investigation of all the tabu parameters together. By varying the tabu parameters simultaneously, the gain in performance in RRC ranged from 22.42 to 23.49%, after which RRC remained fixed as shown in Figure 21.

The second network, which is a linear-type GPS network for the Seychelles, consists of 67 stations as shown in Figure 22. The initial schedule with a cost of

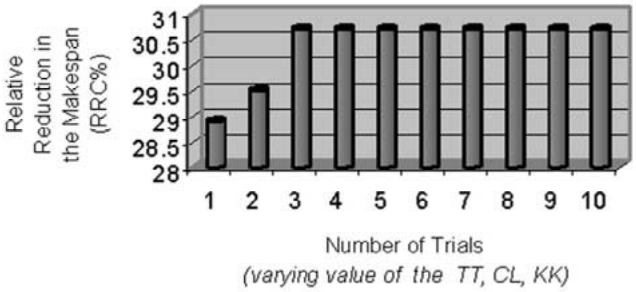

Figure 21. The computational result for varying the CL, TT and KK parameters.

994 min was composed of 71 sessions observed using three receivers [24]. As in the Malta network, the RRC measure has been implemented to evaluate the effect of the tabu parameters on the obtained results in terms of the schedule quality and computational effort. The V_{BFS} with a cost of 933 min is found (see Figure 23) when the tabu parameters are CL =10, TT = 3, and KK = 20. The size of the TL is [71×71]where the number of the observed sessions is 71 as shown in Figure 24. The twin strategy has been applied by individually investigating the tabu parameters or changing their values during the execution of the TS technique. The computational results show that the selected values for these parameters do not affect the solution quality due to the linear type of the GPS Seychelles network. The increased size of the network does not affect the tabu parameters apart from the value of the TL parameter. The size of the TL is dependent on the number of the observed sessions [TL=38×38] for Malta and [TL=71×71] for the Seychelles. The effect of the increased size of the TL to obtain the V_{BFS} can be seen in the increase of the execution time (ET) from 6 s in the Malta network to 40 s in the Seychelles network, as shown in Table 2. More detail about the above can be seen in Saleh [25]

In conclusion, the quality of the schedules obtained by the TS technique does not seem to be affected by the different choices of tabu parameter values and implementation strategies. The TS strategy incorporated into a simple pair-wise exchange procedure appears to be a very effective heuristic technique for GPS surveying. In general, it appears that a better strategy would be to use a small TT parameter, while the use of the fixed length CL parameter offers new ways to avoid extensive computational effort without sacrificing schedule quality. Computational tests show that the values for the TL parameter increase with the size of the network. The robustness of the TS technique seems to be due mainly to the efficiency of the TL strategy. Also, the characteristic of the GPS network architecture plays a crucial part in selecting a feasible starting schedule. The developed technique has been coded in C++ and implemented on a PC (Viglen p5/133).

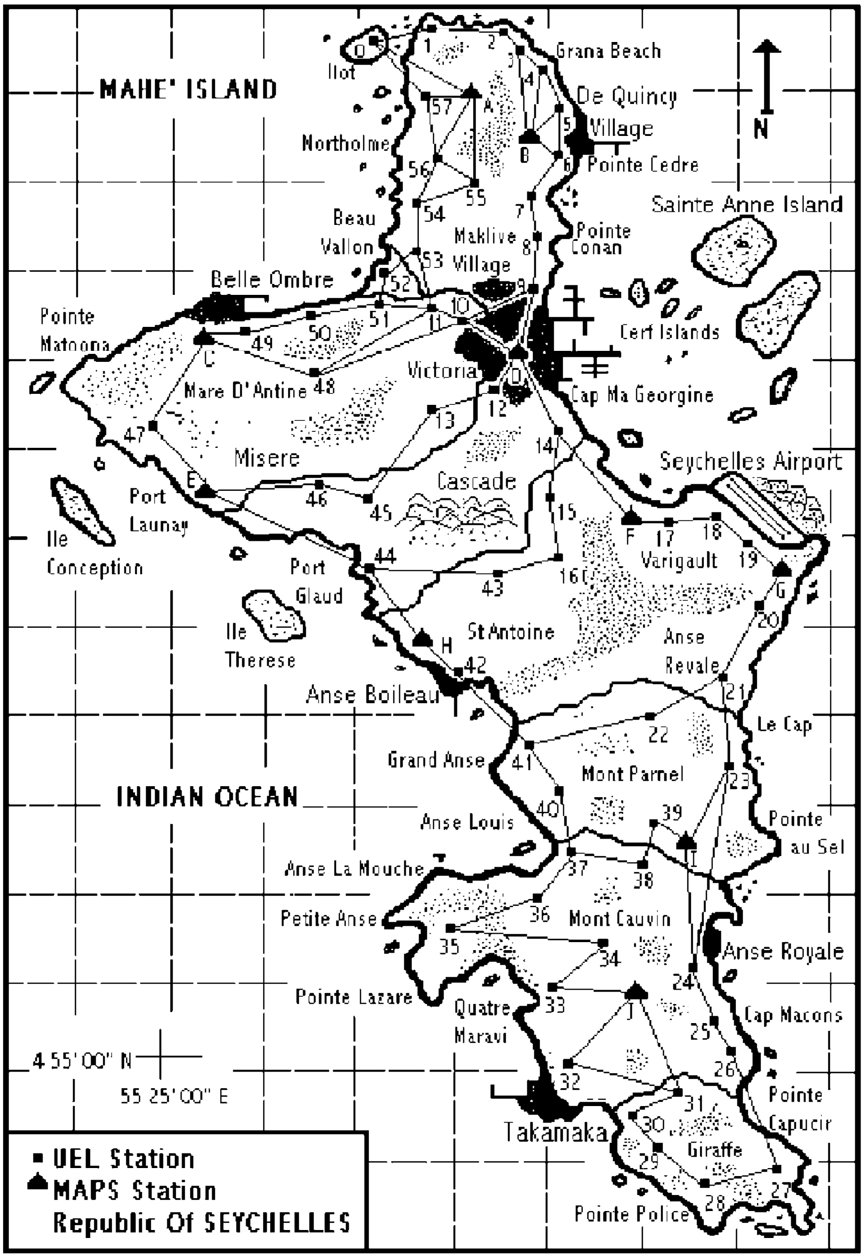

Figure 22. Seychelles GPS survey network.

5. Further use of TS in GPS Surveying

Another application in which the tabu search technique can be successfully implemented is optimisation of ambiguity resolution in GPS data. In this paper, a

Figure 23. The graph of V_{BFS} versus number of iterations KK for TS applied to the GPS Seychelles network.

Table 2. Control parameters of the TS technique applied to different types of GPS networks.

Structural elements and control parameters		Network type	
		Triangulation (Malta)	Traverse (Seychelles)
Observed and computed data	*U*	38	71
	V_{INT}	1405	994
	V_{BFS}	1075	993
	RRC	23.49%	6.14%
	ET	6	40
Selected tabu parameters	TL	38×38	71×71
	TT	3	3
	CL	10	10
	KK	28	20

neighbourhood structure based on the constructive search has been developed. This constructive search suits the static nature of GPS surveying networks. For optimisation of the GPS ambiguity another neighbourhood structure based on the random search is suggested. This random search suits both the dynamic nature of the GPS ambiguity and the strategic oscillation of the TS technique [26]. There are several reasons for considering the use of the dynamic TS technique when optimising ambiguity resolution. Firstly, if the feasible solution space of the problem is disjointed (such as the ambiguity resolution), then strategic oscillation provides a mechanism for crossing regions of infeasibility in the course of searching for optimal solution. Secondly, optimising the ambiguity resolution presents a non-linear complete feasibility problem in addition to its optimality requirement. Thirdly, the CL parameter is a dynamic list which varies according to the status of the current solution. For each iteration, the number of possible exchanges on the CL parameter

```
=0000000000000000000000000000000000000000000000000000000000000000000000
1=000000000000000000000000000000000000000000000000000000000000000000000
00=00000000000000000000000000000000000000000000000000000000000000000000
000=32000000000000000000000000000000000000000000000000000000000000000
0001=000000000000000000000000000000000000000000000000000000000000000000
00020=00000000000000000000000000000000000000000000000000000000000000000
000000=01000000000000000000000000000000000000000000000000000000000000
0000001=000000000000000000000000000000000000000000000000000000000000000
00000010=00000000000000000000000000000000000000000000000000000000000000
000000000=0000000000000000000000000000000000000000000000000000000000000
0000000000=000000000000000000000000000000000000000000000000000000000000
00000000000=00000000000000000000000000000000000000000000000000000000000
000000000001=0000000000000000000000000000000000000000000000000000000000
0000000000000=000000000000000000000000000000000000000000000000000000000
00000000000000=00000000000000000000000000000000000000000000000000000000
000000000000001=0000000000000000000000000000000000000000000000000000000
0000000000000010=000000000000000000000000000000000000000000000000000000
00000000000000000=00000000000000000000000000000000000000000000000000000
000000000000000000=0000000000000000000000000000000000000000000000000000
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000000000000000000000200=0000000000000000000000000000000000000000000000
0000000000000000000000000=000000000000000000000000000000000000000000000
00000000000000000000000000=00000000000000000000000000000000000000000000
100000000000000000000000000=0000000000000000000000000000000000000000000
0000000000000000000000000000=000000000000000000000000000000000000000000
00000000000000000000000000000=00000000000000000000000000000000000000000
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0000000000000000000000000000000000=000000000000000000000000000000000000
00000000000000000000000000000000010=00000000000000000000000000000000000
000000000000000000000000000000000000=0000000000000000000000000000000000
0000000000000000000000000000000000000=000000000000000000000000000000000
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Figure 24. The tabu list structure [71×71].

varies from a few moves to all possible exchanges. By dynamically changing the CL, the efficiency and diversity of the search can be improved.

6. Concluding Remarks

In this paper, a TS technique has been developed which permits the production of a schedule on an optimization basis for GPS networks. The comparison of the performance of the TS technique applied to different types and sizes of GPS networks is reported. The results obtained are encouraging and the ability of the developed TS technique to generate rapidly high-quality solutions for designing GPS networks can be seen.

7. Acknowledgements

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*Disclaimer:*The information provided in this paper is the sole responsibility of the authors and does not reflect the European Commission’s opinion. The Commission is not responsible for any use that might be made of data appearing in this publication

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