TABU SEARCH FOR TARGET-RADAR ALLOCATION

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Abstract: In this paper the problem of allocating air-defence illumination radars to enemy targets is presented. A Tabu Search metaheuristic solution is described and the results achieved are compared to those of other heuristic approaches. Implementation and experimental aspects are discussed. It is argued that Tabu Search could be used in near realtime decision making systems.

Keywords: Combinatorial optimization, metaheuristics, Tabu Search, allocation.

1 Introduction

In case of an enemy airraid an air defence system should engage enemy fighters, helicopters etc. with the available missiles so that the most threatening and valuable enemy targets are engaged first. Since the air picture is changing constantly, the allocation of the missiles to the wanted targets must be continuously updated. Unfortunately the updating is non-trivial because even for relative small problems, the missiles, the controlling radars, and the targets can be combined in a huge number of ways during a time period.

In addition the optimal solution does not necessarily have to include all the targets and the targets included must be allocated during specific time windows as they enter or exit the effective range of the system.

The complex nature of this allocation problem and the fact, that a solution must be found within a strict time span in order to keep the allocation up-to-date with the air picture, makes it a very interesting combinatorial optimization problem.

Such a problem is approached using heuristic principles (see Silver el al. (1980)) due to its complexity that makes any global approach unsuitable. Moreover, metaheuristic approaches as Local Search, Tabu Search, Simulated Annealing, etc. are also used to develop a suitable metaheuristic based solution (see further Glover and Laguna (1993), Vidal (1993), and Pirlot (1992)).

In section 2, an outline of the system in study is presented. In section 3, the target-radar allocation problem is formulated and modelled. A two-step heuristic approach is described in section 4, while section 5 presents the first step based on Tabu Search and section 6 presents the second step based on Steepest Ascent. Section 7 presents our numerical results obtained in a series of experiments. Section 8 presents improvements in the developed procedure. Section 9 gives some results of experimentations on the problem of quality vs. time usage. Finally, the last section presents our final conclusions.

2 The DEHAWK system

DEHAWK is a modernization program of the Danish HAWK air-defence missile units (see further Cullen and Foss (1998)). This paper will discuss a simplified DEHAWK system looking only at two types of units: the illumination radars (denoted HIPIR's, HIgh-Power Illumination Radar) and the HAWK missiles. Note that the names HAWK and DEHAWK are used interchangeable and both refer to the updated system.

A DEHAWK battery will usually have two HIPIR's, while a batalion will control up to four batteries and thus 8 HIPIR's.

The HAWK system is classified as a medium range air defence system. If a target is to be engaged by a HAWK missile, the target has to be illuminated by one of the HIPIR radar. This means that the HIPIR starts tracking the target by continuously keeping it the target of the radaremission. Some of the emission is reflected from the target and is picked up by the HAWK missile, which uses it to keep the guidance against the target. The process is sketched in figure 1.

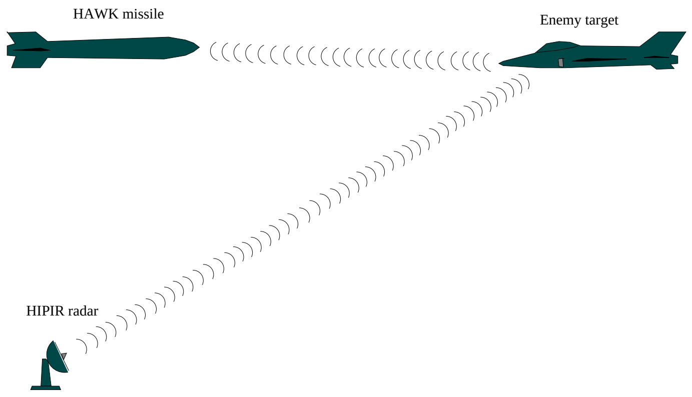

Figure 1: The HAWK guidance system

In general, air defense units are made up of *firing units* which will be denoted FU's. A FU is the smallest unit which independently can engage a target. Since the guidance method limits a HAWK squadron to only have two HAWK engagements running at the same time (i.e. one for each HIPIR), the HIPIR's can be seen as the FU's.

An *engagement* will denote the time sequence of allocating a single target, firing at it, until it has been determined whether or not the target was hit. The time period where it is possible for one of the FU's to engage the target is denoted the *engagement area*

The attacking side sending the air raid will be known a the orange side, while the defending side, using the HAWK system, is the blue side.

When engaging you have a certain probability of shooting down the target depending upon various factors – e.g. the range. This probability will in this paper be denoted *Pkill*. At the time the engagement ends, a successful outcome will mean a benefit for the blue side. This benefit, denoted the *military value* in this paper, must be specified by the user. It usually depends upon the threat it constitutes to the blue at the specific time.

3 Problem formulation

The target-radar allocation problem can be formulated as: In a specific time period, called the *planning period*, to decide which targets to be engaged, at which time, and which HIPIR to be used for controlling the missiles flight. The length of the planning period can vary, but it is usually chosen to be between 2 and 5 minutes.

The allocation has to be updated continuously according to changes in the target course and speed. Therefore the procedure for solving the described problem must calculate a new allocation plan every time the search radar has finished a rotation. During a single rotation the information about all targets in the airspace is updated. Since a rotation only takes about 3 seconds, the time span, within which the allocation plan should be calculated, is very strict.

For the sake of simplicity the missile launcher allocation part has been omitted. In addition the functions for calculating Pkill, the missile flighttimes, and the military values for targets have been simplified.

In order to evaluate whether a procedure can be accepted, there must be specified some criteria. Some of the criteria are *strong*, meaning that they should always be achieved.

For this problem the strong criteria are:

- Speed: The procedure must return a solution within the 3-second time limit
- Maximizing: The mean expected value of the objective function should be within 5 % of the global optimum

A set of weak criteria can be defined too. They describe desirable but not demanded properties of the procedure. The following weak criteria have been defined for this problem:

- Range: The number of targets which come within their own firing range of a blue target before being engaged, should be minimized
- Robustness: The algorithm should, when run real-time, not change the recommended solution for every new 3-second run unless targets are maneuvering or new targets appear

The first of the weak criteria can possible be chained to the strong criterion of maximization of the objective value by a suitable definition of the objective function. The robustness criterion is included because the users of the system would loose confidence in a system that for every 3-second period makes changes in its recommended allocation plan.

For the sake of comprehendeness let us formulate our problem as a mathematical model.

In the model the following indices are used:

$i = 1, 2, ..., n$ denotes a target from the list of targets.

$j = 1, 2, ..., m$ denotes the HIPIR used to illuminate the target.

$k = 1, 2, ..., o$ denotes the specific missile used for an engagement.

The decision variables to be determined are:

$t_{ijk} \in \mathbb{R}$ denotes the time where the firebutton is pressed for missile k to engage target i controlled by HIPIR j.

$x_{ijk} \in \{0, 1\}$ denotes if 1 that the engagement including target i, HIPIR j, and missile k is included in the allocation plan for the planned period.

The following functions are used in the model:

$mv(t_{ijk})$ calculates the military value of target i if engaged by missile k at the time t_{ijk}.

$Pk(t_{ijk})$ calculates the Pkill of target i if engaged by missile k at t_{ijk}.

$f(t_{ijk})$ returns the time of the intercept of target i using missile k launched at t_{ijk} and controlled by HIPIR j.

In addition the following parameters are defined:

eng_start_{ij} is the first time where the firebutton can be pressed to engage target i – i.e. i enters the intercept area of HIPIR j.

eng_end_{ij} denotes the time where target i exits the intercept area of HIPIR j.

r_hipir_j is the time where HIPIR j are ready for the first engagement.

t_lk is the reaction time from the decision to shoot is taken and until the firebutton can be pressed due to the radar lock-on time

t_ev is the time from a target is hit and until it has been evaluated whether it was shot down. If not it probably should be reengaged.

For every target, Pkill is the probability of shooting it down at a certain time and the military value is the benefit of the kill if made. The total expected benefit of an allocation plan can be calculated as follows:

$$maximize \qquad \sum_{ijk} (Pk(t_{ijk}) \cdot mv(t_{ijk}))\, x_{ijk} \tag{1}$$

Restriction should ensure:

1. that the targets are engaged within valid intercept areas and that the reaction time will not let a target get out of range before the actual launch.
2. that one HIPIR are not used in more that one simultaneous engagements.
3. that one target is only allocated once in the allocation plan.

See Hindsberger (1998-I) for a more comprehensive description on the military value, the pkill function, engagement area, etc.

The number of HIPIR's, corresponding to the index m, can be up to 8 and it is not unlikely to expect more than 30 targets (index n), of which all should come within the engagement area of a HIPIR during the planning period. Many of the combinations are prohibited in the cases where some targets cannot be engaged within their valid engagement areas, that is not known before the specific combinations have been checked. So the number of combinations in the problem is huge, taken into account, that the timelimit is 3 seconds.

4 A heuristic approach

The target-radar allocation problem is a non-standard non-linear mixed integer problem and is due to the complexity even for small dimensions rather complex to solve using an exact approach.

The complexity of the problem lead to a two-steps heuristic for solving the problem. In the first step the allocation of targets to the HIPIR's is made. I.e. it is decided which target, which should be illuminated by which HIPIR, and the succession each HIPIR should illuminate the targets. The second step optimizes the start time of the engagements assigned to a HIPIR, making the engagements start at the most optimal time. Throughout this paper the engagement start time denotes the time, where the firebuttom is pushed in order to launch a missile for an engagement.

The first step, which is the integer part of the problem, it was decided to solve using general search heuristics, or more specific the neighbourhood-based metaheuristics (see further Pirlot (1992) and Hindsberger (1998-II)). At first in order to get insight about the problem, the most simple of these heuristics - a Steepest Ascent (greedy) heuristic was implemented. From this one can get useful information about the behaviour of the problem and some objective function values, one can compare with the results of the more advanced heuristics.

Of the more advanced neighbourhood-based heuristics, Multistart Descent, Simulated Annealing and Tabu Search were tried, and since all could be based on the neighbourhood function already written for the Steepest Ascent algorithm, implementation were quickly.

For the second step only a continuously version of the Steepest Ascent heuristic was implemented.

The implementation of the two steps including the neighbourhood structures used and Tabu Search memory implementation is described below.

5 Step 1 - Allocation optimization

In figure 2 a pseudo-code of the classic Tabu Search program is shown. The neighbourhood implementation is described below. The *Time_opt* procedure is the second step doing the engagement time optimization and is covered in section 6.

```
begin
  initialization
  $curr\_x := make\_init\_solution$
  $best\_x := curr\_x$
  $best\_obj := Time\_opt(best\_x)$
  $unchanged := 0$
  $k := 0$
  while ($unchanged < max\_unchanged$ and $k < max\_total$) do
    $Y := find\_neighbourhood(curr\_x)$
    $(curr\_x, curr\_obj, tabu) := find\_best(Time\_opt(Y), tabu)$
    if $best\_obj < curr\_obj$ then
      $best\_x := curr\_x$
      $best\_obj := curr\_obj$
      $unchanged := 0$
    else
      $unchanged := unchanged + 1$
    endif
    $k := k + 1$
  end
end
```

Figure 2: Pseudo-code of the Tabu Search main program

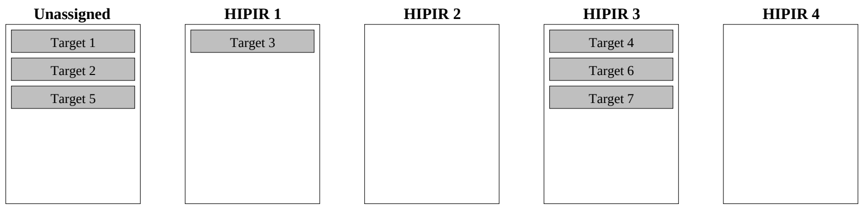

Figure 3: The data-structures where a solution is stored

The function, *find_best*, which evaluates the generated neighbours takes the tabu memory as parameter, returning the best of the neighbours (and the objective function value, $C(x)$ of this) depending on the current recency and frequency memory. Then the current solution are set to this and the tabu memory is updated according to this choice. The best value obtained at this point is updated if the value of $C(x)$ of the new solution is an improvement over this.

A datastructure for storing the allocations of both the current solution and the solutions of the generated neighbours is defined. The basic is the *allocation*-class, which contains all the information about a single allocation, identified with the ID-number of the allocated target. An array of allocations is defined for each HIPIR-radar, containing the allocations of that particular HIPIR. An additional array is defined containing all the non-allocated targets. A sample allocation plan is shown in figure 3. The system shown consist of four HIPIR's and seven targets. Three of the targets are unassigned; target 1, 2, and 5, while target 3 has been assigned to HIPIR 1 and HIPIR 3 should engage target 4, 6 and 7 in this succession.

The initial assignment was chosen always to be the zero-assignment, i.e. the assignment where all target are unassigned, and thus stored in the unassigned array. The stochastic nature of which neighbour generating function, as shown later, will make sure every possible allocation plan can be reached from this assignment. So there was no reason to start with some or all of the targets randomly assigned to the HIPIR's.

The search for a new allocation is done within the while-loop of figure 2. At first a part of the neighbours to the current solution is found. This is done by the neighbour generation function using the neighbourhood definition described below.

5.1 The neighbour generating function

For the implementation it was decided to create a function, which generates a fixed number of neighbours each iteration. The number to be generated can be user-specified, but has an upper limit depending upon the number of HIPIR's and targets.

A neighbour is defined as the move of one target and not as an exchange of targets. If n neighbours are to be generated, only the first one will be randomly chosen, while the $n-1$ next neighbours is defined by a succession, which will be described later.

When picking the first neighbour a random HIPIR (with at least one target assigned to it) to move from is selected. From the array of this a random target to move is drawn. Note that all HIPIR's has an ID number, where 0 denotes the array containing the unassigned targets. If moving from HIPIR 0 (the unassigned) the HIPIR to move to is randomly selected between those with an ID higher than 0. Else the algorithm just pick a random one of all the arrays to decide where to move. If the HIPIR moving from is the same as the one moving to, the neighbours generated are just changes in the succession the HIPIR engages the targets. When the two HIPIR's ID numbers are different, the neighbours generated in this case, are the possible placements of the moving target in the succession of targets assigned to the receiving HIPIR.

The following steps define the succession of the neighbours, once the first one has been selected. The steps are taken until the wanted number of neighbours has been generated. Because of the number of special cases, it might look complicated, but the example below should help to clear out any confusion.

- The selected target is moved to the HIPIR with the next higher ID number, starting over from 0, when the highest number has been reached. If the target is moved from HIPIR 0 (unassigned), the unassigned number is excluded.
- If it has been tried to move the target to all possible HIPIR's, the procedure switches to the next target (in the succession) of the HIPIR moving from. If the last target of that HIPIR has been reached, the HIPIR to move from is switched to the next higher number, again starting over from 0 if the highest ID number has been reached.

Note that each time the HIPIR's or target ID is changed, the number of new neighbours, which can be created, will vary depending upon the current solution.

EXAMPLE 5.1 (THE TABU SEARCH NEIGHBOURHOOD) *Consider the situation where the solution pictured in figure 3 are the current solution and 9 neighbours are to be generated. The first neighbour is chosen the following way:*

- *One of the nonempty HIPIR arrays is chosen to move from – in this case HIPIR 3.*
- *Of the three targets assigned to HIPIR 3, the second target is randomly selected, i.e. the target with ID 6 is to be moved.*
- *Now a HIPIR to move to is chosen. In this case any would do, and HIPIR 2 is randomly picked.*

This gives neighbour 1 pictured in figure 4. If the steps described above are used to pick the next n-1 *neighbours, the neighbours numbered from 2 to 9 in the figure are generated. In neighbour 1 target 6 is moved to HIPIR 2. Since the array of HIPIR 2 is empty, this can only be done in one way. So when generating neighbour 2, the target now has to be moved to the next HIPIR array, which in this case is HIPIR 3 – the one moving from. Since there are more targets assigned to HIPIR 3 than target 6, it can be put in other places in the succession of engagements resulting in neighbour 2 and 3. When coming to the array of unassigned targets, there is no defined succession of those targets. So target 6 is just added to the array making neighbour 5.*

Before all 9 neighbours have been generated, target 6 has been moved to all possible positions. So the algorithm switches to the next target in the succession, which is the next target – if any – assigned to the same HIPIR. In this example it is target 7. So in neighbour 8 and 9 it is target 7 to be moved.

If even more neighbours were generated, target 7 would at a point have been moved to all possible positions too. So the next target in the succession should be used for generating the next neighbours. In this example it is target 1 of the unassigned array, since there is no more targets assigned to HIPIR 3 and no one is assigned to HIPIR 4.

With this neighbourhood definition a neighbour is a small change to the existing solution and it assures that all possible solutions can be reached from any other solution, which are some of the basic properties a neighbourhood should process.

5.2 Implementing memory

As the tabu element either just the moving target or a combination of the receiving HIPIR and the moving target can be used. E.g. if target 6 just has been moved from HIPIR 3 to HIPIR 2, either the moving of target 6 (no matter where-to) or the moving of target 6 (no matter from which HIPIR) to HIPIR 2 is declared as tabu for the next *tabulength* iterations.

Both of the above mentioned tabu structures have been implemented in order to see any differences in performance. The frequency memory is implemented too and has to fit the tabu structure used. So in the first case the penalty added to $C(x)$ is a certain percent of the times the target has been moved, while in the other case some percent of the times the target has been moved to that specific HIPIR. The percent is user-specified in both implementations.

EXAMPLE 5.2 (THE TABU SEARCH FREQUENCY MEMORY) *The frequency memory is used to diverge the search into new areas. In this case it is implemented as a penalty to the objective function. The penalty added to the objective function is an userspecified percentage of the number of times the move to the investigated neighbour already has been taken. If 10 % has been specified and the number of times target 6 has been moved is 10, $C(x)$ of the neighbour describing this move, will be lowered by 1. If target 6 had been moved 100 times the penalty would be 10 instead, making the less taken moves more interesting.*

In addition to the frequency penalty both the tabu length, the number of neighbours generated, and the parameters of the stopping criterion (fixed time or fixed number of iterations) are user-specified, making it possible and easy to test the dependence of those parameters. In this implementation the tabu length was fixed for the duration of a computation run.

5.3 The objective function

When the best of the neighbours is to be found the change in the objective function value $C(x)$ that each neighbour results in is calculated. $C(x)$ was defined as the sum of the military value of a target times the probability of shooting that specific target down. Since both of those again depends upon the time the missile hits (or misses) the target, you have to pick the most *optimal time* of each engagement to start. This is done by the *Time_opt* procedure described below, where the *optimal time* also will be defined.

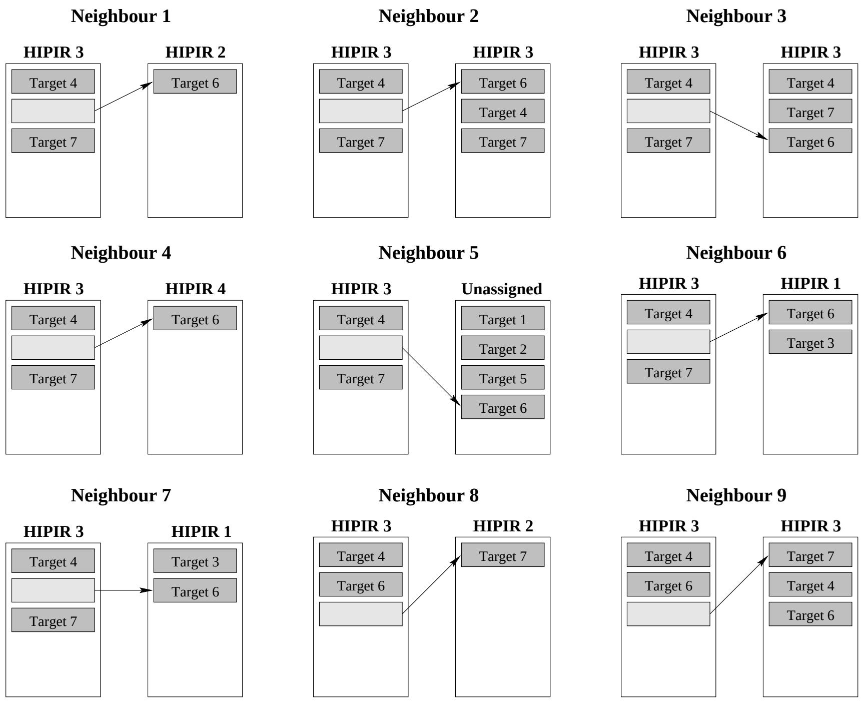

Figure 4: Neighbours generated in Tabu Search

6 Step 2 - Time optimization

In order to find the optimal start time of the engagements of a HIPIR, this procedure is used. Using a nontrivial neighbourhood, it features the Steepest Ascent method, since all possible neighbours are checked each iteration. A pseudo-code of the procedure can be seen in figure 5 .

```
procedure Time optimization
check_if_possible
if no_of_targets = 1 then
   update(assign)
else
  begin
    initialization
    change := true
    while change do
      change := false
      for i := 1 to no_of_targets do
        imp1 := move_forward_check(i)
        imp2 := move_backward_check(i)
        improvement := max(imp1,imp2)
        if improvement > 0 then
          update(assign)
          change := true
        endif
      end
    end
  end
```

Figure 5: Pseudo-code of the time optimization procedure

When the procedure is called, it has to make sure it is possible within the allowed planning time to engage all the assigned targets. The *check_if_possible* procedure will do this as well as put the assignments in a tight succession, which is the succession, where each engagement starts as soon as the previous engagement is finished. This solution is the initial solution of the algorithm, but since it is not necessary the optimal time allocation, it has to be tested whether some targets could be engaged at more optimal times improving $C(x)$ this way.

6.1 Optimal time - critical line

The *optimal time* for an engagement refers normally the time where an engagement should be started, in order to have the highest probability of shooting down the target. An exception is, if a target has crossed the critical line before it is hit by a missile fired at the optimal time using the definition above. In this case the optimal time instead denotes the engagement start time to be used, so the target is hit as it reaches the critical line. This is done in order make the algorithm engage the targets before they cross the critical line if possible, which was one of the properties the algorithm should fulfil.

6.2 Neighbourhood generation

When only one target is allocated to a HIPIR, it is easy. A precalculated table contains the optimal start time of an engagement for each target-radar combination. So this start time is used unless it is later than the planning time allows. In this case the target is engaged at the latest time possible instead.

With more than one target assigned it becomes more complicated, since the engagements can block for each other, so one or more of them cannot be engaged at the optimal time. Three points of time are defined for each target. The earliest possible, EST, the optimal, OST, and the latest possible engagement start time, LST. The first and the last of those can change as the engagement start time of either the previous or the next engagement is changed, but they will never cross the boundaries of the possible intercept period. It should be noted that the optimal engagement start time does not necessary lie between the other two, as seen for the third engagement of figure 6. In this figure engagement 2 and 3 block for each other.

When such a blocking occurs between two engagements, a boolean variable will be set for use in the moves explained below.

The main part of the *time_opt* procedure is the *for*-loop, which for every assigned target, will calculate the change in $C(x)$ for each of the possible, following moves:

Forward move: The engagement is delayed, if the engagement is not blocked by the next and either the engagement start time is less than the optimal of that target-radar combination or it is blocking for the previous engagement to move forward.

Backward move: The engagement is started earlier, if the engagement is not blocked by the previous and either the current start time is greater than the optimal of that target-radar combination or it is blocking for the next engagement to move backward.

The most promising "move" can now be found, as the one with the greatest positive change to $C(x)$. Since all possible neighbours are tested, this is a Steepest Ascent algorithm. So until no improvement can be found for any of the targets, the loop above is repeated.

This neighbourhood definition should both make a neighbour a small change compared to the existing solution as well as ensuring all "optimal" solutions can be reached within a finite number of iteration from any other solution. The notation "optimal" is used, since not all possible time displacements are defined in this implementation. But the ones defined should, with the assumption described below, include the optimal solution.

The assumption that has been made is, that the increase or decrease rate of the benefit value of each target (i.e. the Pkill times the military value) is constant between EST, OST, and LST as shown in figure 7.

With the mentioned assumption the optimal solution is still contained in the solution space. This can be seen this way. If no blockings occur, the optimal solution is included, since all OST points are included. If a blocking occurs as the one in figure 6, both of the start times are tried to be moved ΔT forward as shown in figure 8. If the gain in benefit of engagement 2 is greater than the loss of benefit of engagement 3, ΔT should be as great as possible, which is the greater of the intervals $[EST2, LST2]$ and $[EST3, LST3]$. If the gain is less than the loss, ΔT should be zero, and if equal ΔT could be any of the two values. Since all the EST and LST points are included in the solution space, the optimal solution will be contained in this, because of the assumption of constant increase/decrease rates.

During the testing this procedure turned out to be very good in finding the global optimal solution since only in rare occasions an assignment blocked for another, which could have improved the solution.

After the time optimization the partial objective function value of the used HIPIR is stored in memory and used by the *find_best* procedure to find the best of the generated neighbours.

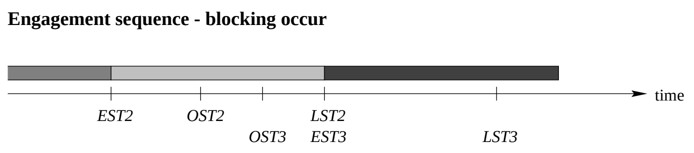

Figure 6: A sequence of engagements where a blocking occurs, since the EST of the last engagement is later than the OST

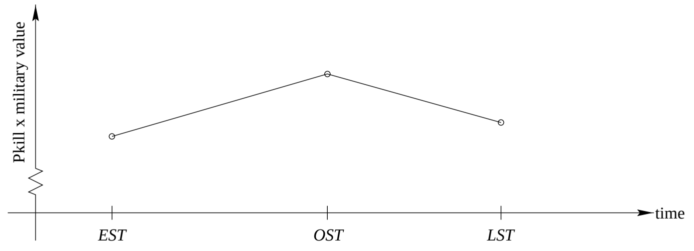

Figure 7: For the implementation it has been assumed, that the increase or decrease rates between the points are constant as shown in the graph

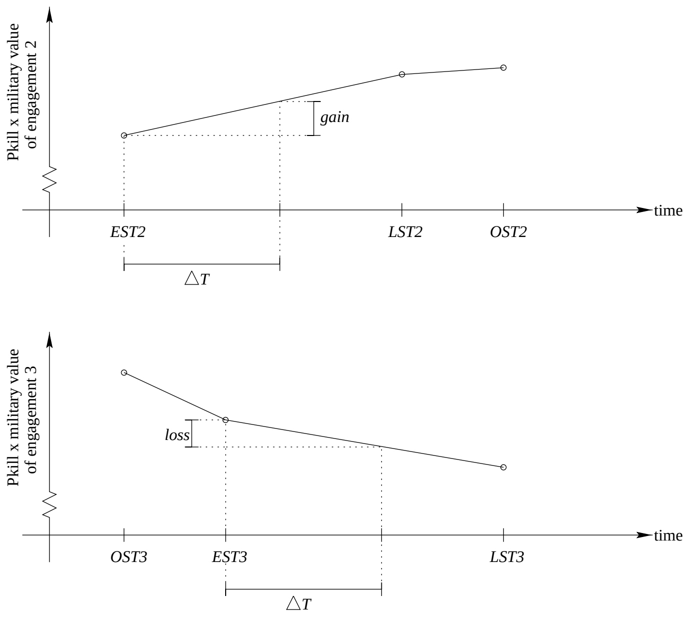
Pkill x military value of engagement 2
gain
time
EST2
LST2
OST2
$\triangle T$
Pkill x military value of engagement 3
loss
time
OST3
EST3
LST3
$\triangle T$

Figure 8: The upper plot shows the benefit of engagement 2 of figure 6 while the lower is the benefit of engagement 3

7 Experiments

The stochastic nature of the algorithms make them in general return different solutions to the same problem. In order to find the expected value of $C(x)$ of the algorithms for a given scenario, an automated program was written. This ran the algorithm a user-specified number of times with the same parameters, except for the random number seed, calculating the sample mean value and variance of $C(x)$ and the computation time used.

The results shown in this paper are unless otherwise stated a sample mean value of such a batch-run. All the computations was done on a Digital VAXstation 4000-60 workstation.

It was initially assumed that a 100 times improvement in the computation time could be gained, if the algorithms were reprogrammed i C++ and run on a modern workstation. Therefore the algorithms were allowed to run for 300 seconds in the tests, and were still assumed to be within the time limit of 3 seconds.

7.1 Test scenarios

The algorithms were tested on various scenarios, which had a different number of targets and HIPIR's. A scenario with two HIPIR's and seven targets will in this paper be denoted as a 2-7 scenario, while a scenario with 8 HIPIR's and 13 targets thus is denoted an 8-13 scenario. The density of a scenario describes the number of targets compared to the number of HIPIR's. A 2-13 scenario is considered dense while an 8-7 scenario is sparse. The size of a scenario depends both on the number of HIPIR's and the number of targets. A scenario will in most cases be considered small, if it has less than ten targets or four HIPIR's.

In all scenarios the HIPIR's were located in pairs and the targets incoming were all being jet fighters. The planning time was set to 200 seconds.

For none of the scenarios the global optimal value of $C(x)$ is known for sure. So the mean values obtained will be compared with the best value of $C(x)$ found for that particular scenario, which should be very close to, if not the global optimum. For the 2-13 and the 8-13 scenario, which will be used most widely, the best values found were 247.73 and 482.67 respectively and the "optimal" value will in this paper, when mentioned, refer to one of these values.

7.2 Tabu Search results

As described in the last section, two versions of Tabu Search were implemented with the tabu definition being the difference. The one denoted TS-simple uses the "simple" tabu definition with only having the moving target as the tabu element, while the other, TS-advanced, uses the more advanced definition having the tabu element as a combination of the moving target and the receiving HIPIR.

For the first experiments the stopping criterion was to stop after uc unchanged iterations. Initial testing showed that $uc = 80$ would result in the most efficient search. Experiments to assess the influence on the two algorithms from the number of neighbours generated and the length of the tabu list (i.e. the tabulength) were made then, keeping the frequency penalty and the uc constant.

When using the simple tabu definition a 10 % frequency penalty was used, since only 13 tabu element exist, being the 13 targets. This value was a guess but from the earlier results achieved by the other methods, neighbours often differed less than 0.5 in their values of $C(x)$, so the 10 % penalty should be sufficient to diverge the search to other areas, while still being small enough not to disrupt the basic search with "noise".

When using the advanced definition the number of tabu elements was 8×13, so the penalty was for this definition increased to 100 % for similar reasons as above.

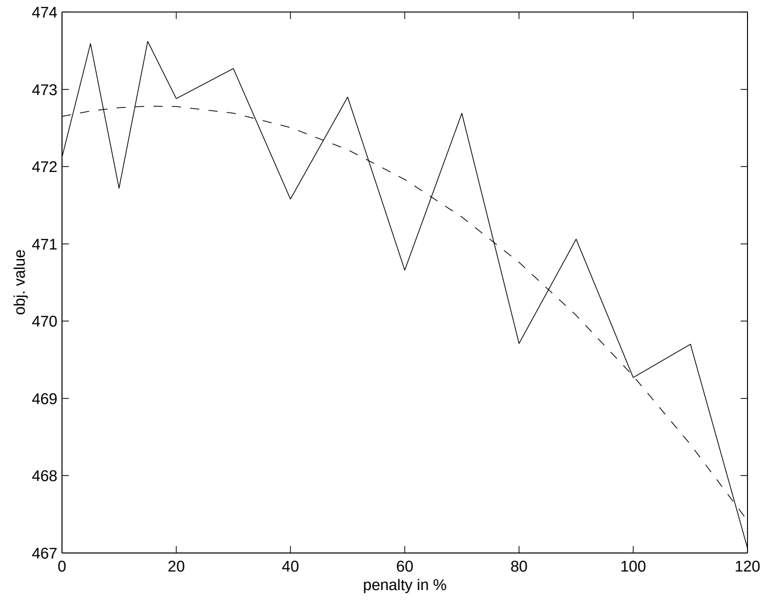

Figure 9: The dependence of the penalty-% for TS-simple using the 8-13 scenario

With all other parametres fixed, the frequency penalty were varied, to see if the values used until now actual were the optimal. While TS-simple turned out to do better using a penalty of 15 % rather than the previous used of 10 %, the 100 % penalty used by TS-advanced looked optimal. The results when using TS-simple on the 8-13 scenario can be read from the graph in figure 9. The dashed line is the fittet polynomium of 2nd degree.

Table 2 shows the best values of the tabulength (denoted $\mid T \mid$), the number of neighbours generated at each iteration (NB), and the frequency penalty (% penalty) for the two different versions of TS used on the 2-13 and the 8-13 scenario.

Looking at the tables 1 and 2 is seen that the actual performance of TS-simple is similar to that of TS-advanced. The optimal numbers of neighbours to be generated might look high, but experiments showed that with a lower number of neighbours generated – where more iterations can be performed instead – the algorithms come out with inferior solutions.

7.3 Comparison with other methods

A total of 5 different algorithms were implemented: A Local Search algorithm (LS-Single), performing *one* search, the same algorithm performing searches for the time available (LS-Multi), a Simulated Annealing algorithm (SA), as well as TS-Simple, and TS-Advanced. For a thoughfully presentation of these approaches see Hindsberger (1998-I). For a fair comparison of the algorithms, they were run for a fixed 300 CPU-seconds period (of which LS-Single only used a few seconds). The algorithms were tried using both the 2-13 and the 8-13 scenario as before, in order to see any dependence of the scenario density. Note that the results in this section are based on 50 runs of each and not the 100 as used by the test program earlier in this section.

Scenario	ID	mean	s. dev.	max	min	% best
2-13	1	227.14	8.78	247.56	205.42	8.31
	2	229.01	9.04	247.73	208.83	7.56
8-13	3	473.62	6.86	482.67	449.89	1.87
	4	472.77	6.91	482.03	438.58	2.05

Table 1: Statistics on of some of the best TS runs. The ID numbers refer to the parameter values shown in table 2 below

ID	Scenario	method	NB	$\mid T \mid$	% penalty
1	2-13	TS-simple	16	8	15
2	2-13	TS-advanced	16	12	100
3	8-13	TS-simple	34	4	15
4	8-13	TS-advanced	34	12	100

Table 2: Table showing the parameters used in table 1. NB denotes the number of neighbours generated, $\mid T \mid$ denotes the tabu list length and the % penalty, the penalty to the frequency memory

The parameters used are the same as the ones found to work best below 300 seconds in average computation time. For the two Tabu Search algorithms they are the ones shown in table 2. When now running for a fixed period, the individual runs, which took longer without the time limit should return inferior solutions, while the ones finished before the 300 seconds might obtain better results. As it can be seen later in table 3 and 4, the mean value of $C(x)$ is actually almost unchanged.

Tables of the descriptive statistics of $C(x)$ obtained using the different methods are shown in table 3 and 4, while boxplots showing the distributions for comparison can be found in figure 10 and 11. LSS and LSM denote the LS-Single and LS-Multi methods, while TSS and TSA denote the TS-Simple respectively TS-Advanced methods.

Method	mean	s. dev.	max	min	% best
LS-single	195.46	20.12	241.63	155.02	21.10
LS-multi	230.40	6.45	245.44	218.87	7.00
SA	218.18	13.45	246.30	185.93	11.93
TS-simple	233.31	6.93	247.56	221.97	5.82
TS-advanced	235.08	6.53	247.73	222.14	5.11

Table 3: Descriptive statistics of the different algorithms when applied to the 2-13 scenario

Method	mean	s. dev.	max	min	% best
LS-single	453.84	16.09	478.52	419.00	5.97
LS-multi	473.51	3.89	482.62	464.21	1.90
SA	465.92	8.72	480.00	440.10	3.47
TS-simple	475.21	4.56	482.67	459.66	1.55
TS-advanced	472.41	5.27	480.81	457.36	2.13

Table 4: Descriptive statistics of the different algorithms when applied to the 8-13 scenario

From the tables and figures it is concluded that TS-advanced is the best suited algorithm overall, since it is the best for dense scenarios and comparable with every other in the more sparse scenarios. Both TS-simple and LS-multi are very close in the results though. SA as implemented is somewhat inferior, especially for the dense scenarios. It looks like the dense scenarios have a solutions space more ill-suited for the metaheuristics in general and SA in particular. LS-single was as expected the worst and is far from the others in all aspects.

As the results show, non of the methods fulfil the property set up in section 3 of having the mean value of $C(x)$ to be within 5 % of the optimal value for all scenarios. TS-advanced almost makes it though. In the next section various improvements to help the TSA algorithm to fulfil the mentioned criterion will be discussed.

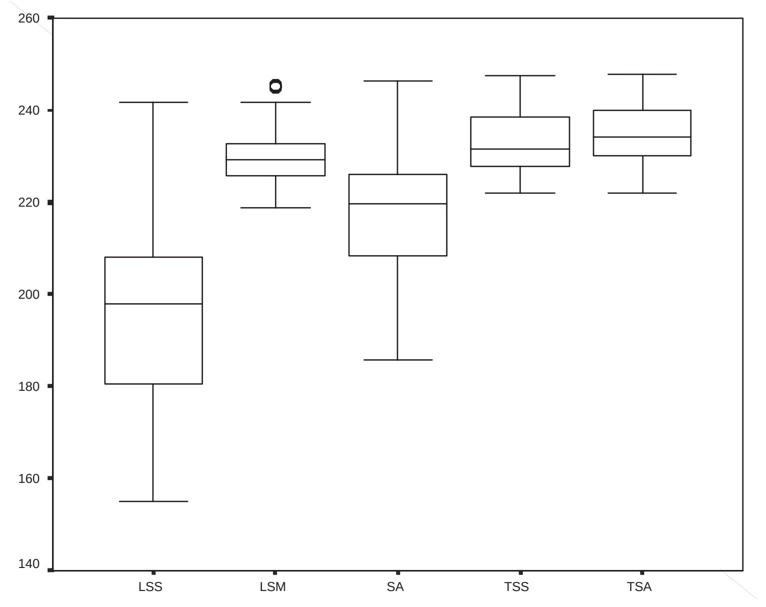

Figure 10: Boxplot showing the performance of the different algorithms applied to the 2-13 scenario and with parameters as described in table 2

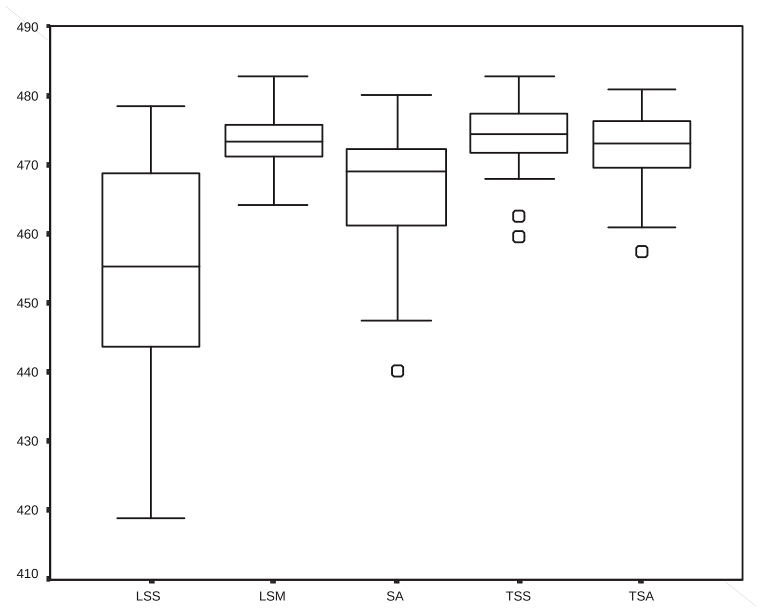

Figure 11: Boxplot showing the performance of the different algorithms applied to the 8-13 scenario and with parameters as described in table 2

8 Improving the Tabu Search algorithms

The five algorithms described above were all improved in different ways. Best results were gained for the two TS algorithms.

8.1 No logfile generation

The TS-Advanced version was stripped for every output command, except for the showing of the final allocation plan. When solving the 2-13 scenario a 23.5 % improvement of the mean number of iterations performed was achieved, increasing the sample mean of $C(x)$ with about 0.6 % as seen in the table 5. Used on the 8-13 scenario, the number of iterations performed within the time limit once again was improved by 23.5 %, while this meant less to the achieved mean value of $C(x)$, which this time only was raised by 0.2 %.

Scenario	method	$C(x)$	iterations	*time_opt*'s
2-13	TSA normal	235.08	497.20	8669.40
	TSA -out	236.56	614.06	10725.10
8-13	TSA normal	472.41	210.16	11805.64
	TSA -out	473.31	267.86	15077.18

Table 5: The gain when writing no logfile (-out). The columns show the mean values of the results

8.2 Tabu list clearance

As the Tabu Search algorithms were implemented, the tabu list would never be cleared. When a new best solution were found, a tabu element might therefore block for an effective local search performed from this solution and thus the possibility of finding an even better solution the next iteration could be missed.

In order to solve this the TS-Advanced implementation was changed so the tabu list was cleared every time a better solution was found. This turned out to make the search for optima more efficient. As it can be seen in table 6, $C(x)$ was improved with 2.19 % and 0.44 % compared to the non-changed algorithm, when used on the 2-13 respectively the 8-13 scenario.

If the output logging were removed too, as earlier described, the results were even better though not that much.

Scenario	method	mean	s. dev.	max	min	% best
2-13	TSA	235.08	5.27	247.73	222.14	5.11
	TSA cl	240.24	5.34	247.73	224.20	3.02
	TSA cl -out	240.29	5.19	247.73	227.38	3.00
8-13	TSA	472.41	5.27	480.81	457.36	2.13
	TSA cl	474.47	5.73	482.62	461.33	1.70
	TSA cl -out	475.89	3.73	479.81	438.11	1.40

Table 6: Table showing the statistics of $C(x)$ using tabu list clearance

For both the scenarios this means that the wanted quality properties defined in section 3, which the algorithms should fulfil, now are achieved since the mean value of $C(x)$ are below 5 % from the "optimal" value.

9 Quality vs. time usage

With this 'final' algorithm (the TS-Advanced with modified *military value* calculation) it was now tested how mush the CPU-time used actual meant to the quality of the result. As usual it was tested on both the 2-13 and the 8-13 scenario, but the *military value*-function of the algorithm was changed at this point, to make the results more comparable with those of the actual airforce algorithm. As a result of the change the C(x) values obtained were higher with the standard deviation somewhat lower. Therefore the results in this section cannot be compared to those previous shown.

The results can be seen in the graphs in figure 12 and 13. In those the horizontal lines represents the objective value respectively 1 % and 2 % from the best achieved solution.

As shown will just a 10 times improvement in computation time (i.e. allowing 30 secs.) still give results far better that the 5 % limit initial demanded. And with a 60 times improvement (about 180 secs.) the results for both scenarios are within 1 % of the probably optimal value.

10 Conclusions

Due to the complexity of the target-radar allocation problem, the neighbourhood generation for both the implemented optimization parts was complicated and thus time consuming, due to the many special cases. In addition the time to solve the problem was very limited. So this was not the most usual situation to use a metaheuristic approach on, though it for the same reasons, made it interesting to see the performance of the metaheuristic methods in this uncommon environment.

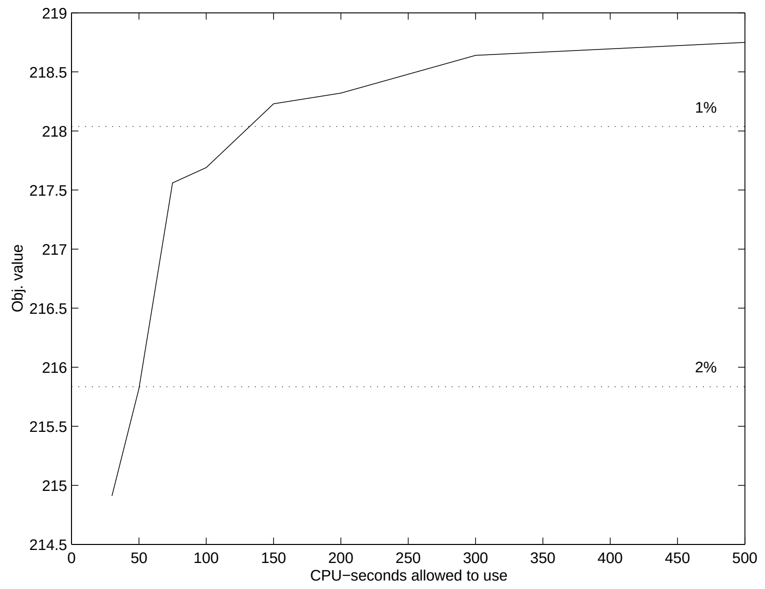

Figure 12: Time vs. quality for TSA used on the 2-13 scenario

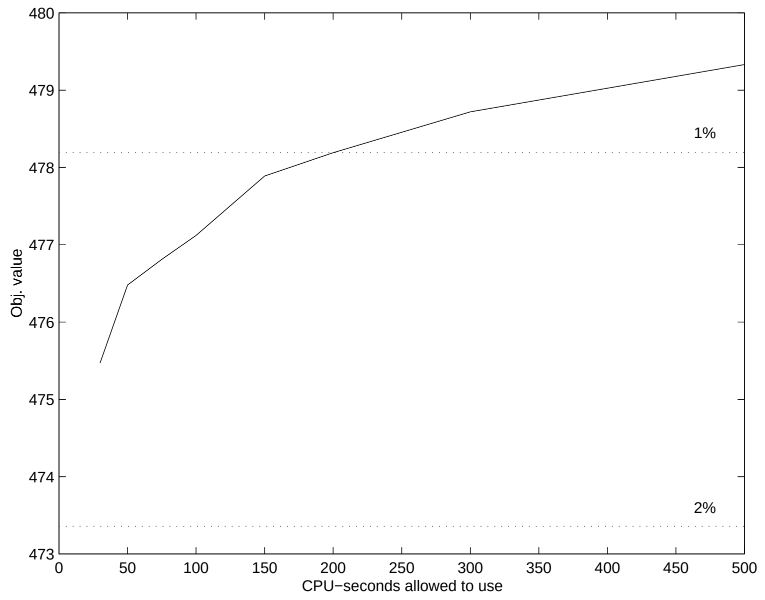

Figure 13: Time vs. quality for TSA used of the 8-13 scenario

From the results it is concluded that TS-advanced is the best of the metaheuristics implemented with TS-simple and LS-multi close behind. For SA too little time was available to work properly, probably since cooling should happen faster than it was effective for the solution space of the problem, especially with that of high-density scenarios.

The results were compared to those of the officially chosen airforce algorithm. Unfortunately due to differences in the defined strong and weak criteria an actual comparison between the TS-advanced algorithm and the airforce algorithm was impossible. The problem was that the defined objective function, which TS-advanced was best to maximize, did not ensured that the targets - if possible - were intercepted before the were able to fire back. And this specific property is valued very high by the Danish Airforce. More on this can be found in Hindsberger (1998-I).

Looking at the criteria defined back in section 3, the following conclusions can be made:

- Speed: If just a 10 times decrease in the computation time can be achieved, this property is complied with with the quality property still complied with, and it should be possible just using modern hardware. Implementing in assembler or C++ code would increase speed even more.

- Maximizing: It was demanded that the expected value of the objective function was within 5 % of the global optimum. TS-advanced complied with this property and had, when modified for using the modified military value calculation, a large margin to the 5 % demanded for all tested scenarios.
- Range: Whether the critical line was crossed by any targets before being intercepted, was not researched that much. This was because it initially was expected that a maximization of the defined objective function would take care of this too. As mentioned it turned out not to be the case, and this is something, which should be worked on in the future.
- Robustness: This property is not relevant when performing a single run, since this is a static situation. None of the metaheuristics implemented were ready to run in a dynamic system updating the allocation plan for every 3-second period. Keeping the solution stable in such a system can be achieved by using the previous solution as the initial for the next run. This is an area were further research can be done.

In general the results were promising and better than expected. So at least on this problem - though the problem was not that well suited - a metaheuristic solution could be used with acceptable results. It might therefore also be true for other problems with similar characteristics.

Acknowledgements

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