Budapest University of Technology and Economics
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Conformance Test Suite Optimization

PhD thesis summary

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1 Introduction

There is an increasing need nowadays for efficient testing of complex telecommunication equipments. That is the reason the ISO and ITU issued the methodology of conformance testing ([ISO9646, Bush90, Baum94]).

The practical part of conformance testing is carried out in test laboratories, where a standardized Abstract Test Suite (ATS) is run on the Implementation Under Test in order to check whether it conforms to the standards. These test suites contain a large number of tests, called Test Cases, which are grouped with other test cases to test groups.

A complete testing, meaning running every test case on the given implementation could take several weeks or months. In such a case, the test laboratory estimates which percentage of the test cases they can run within the given time limit, and select a test set which will be executed.

Since, to my best knowledge, this selection does not contain any theoretical considerations, our aim was to create a theoretically sound methodology of this kind of selection.

I divided my results into three parts. In the first, I show the possibility of the automatism in the test selection problem by introducing the subpurposes and the usage of the data elements. In the second part, I introduce a new model which let us handle the test selection problem mathematically. The third part deals with searching for the optimal or nearly optimal solutions, using several algorithms.

Finally, the list of references and my publications conclude this summary.

2 Research objectives

The motivation behind my research was to make practical conformance testing done in test laboratories ([Heijink94]) more efficient and faster by selecting an optimal test set from a given test suite.

The selection from an ATS is necessary because the test suites issued by the standardization institutes are manually written, that is, no automated test case generation method was used during the creation of the test suite.

During testing, the test laboratories select the test cases for execution from the standardized test suite, depending on their circumstances and their preferences. The method I developed, can replace this subjective selection, making reproducible, controllable, and more efficient but does not rule out the possibility of taking particular preferences into account.

3 Research methodology

In my research, my aim was to solve a practical problem with a theoretically sound method, so first I set up a new mathematical model using the techniques of operations research ([Nemhauser98, Wolsey98]). After formulating the problem mathematically, I solved it by employing well known heuristic methods. I worked out my own algorithms for the test selection problem, including a Tabu Search, a Simulated Annealing, Genetic Algorithms approaches and greedy algorithms. To evaluate the results I used a greedy simulation of the human selection as well as estimations of experts.

4 Background

Although several different approaches exist to optimize the procedure of conformance testing, such a method that both meets the demand of the test laboratories for a usable, practical method, that can be applied to real-life protocols, and has a theoretical background, is still lacking.

Such a conformance test optimization method should satisfy the following demands:

- It is in harmony with the standardized conformance testing methodology
- It is usable for real-life protocols
- It is as executed automatically as possible
- It is applicable to different protocols
- It is applicable to different types of protocol standards issued by different standardization institutes

- It uses standardized test suites and test purposes

The existing approaches focus on test generation. Their goal, in summary is to generate optimal test suites from the protocol specifications, that is, such that contain as few parallelism as possible. The most widely studied model of this kind of optimization is the Finite State Machine (FSM). It is most suitable to obtain theoretical results because it is easy to apply mathematical procedures to it. If an FSM model of the protocol is already given, then there are several algorithms for generating test suites of different error detection capabilities ([Bosik91, Chow78, Dahbura90, Gonenc70, Sabnani88, Sarikaya82, Sidhu89, Sun97]). These algorithms, however, are hardly applied to real life protocols because of the large number of states in the FSM model.

Another approach of test generation, which is not based on FSM, is the metric based test selection. It defines a metric space over the behaviour space of the protocol made of *execution sequences*, then select an ε-dense subset of the original set of the test cases. This selection is based on the *distances* of execution sequences. An execution sequence can be represented as a set of pairs (a_k, α_k) where a_k is an event and, α_k is its recursion depth $(k = 1, \ldots, K)$. The distance of two execution sequences is a representation of their difference ([Vuong92, Vuong97, Zhu97]).

The problem with the FSM-based methods is that it is usually not possible to create a usable FSM model of real-life protocols because of their complexity. A solution to this problem could be the conversion of the test generation methods into ones that use the Extended Finite State Machine (EFSM), but this conversion generates new, so far unresolved problems. The metric based selection also presents problems because the execution sequences are paths in the tree made of the whole test suite. Conformance testing is, however, a black-box testing, thus we cannot determine in advance the paths the implementation will walk on during the testing. My proposed approach, in the contrary, is based on the formal specification of the ATS because it is generally available.

In practice, the test laboratories use the standardized test suites and try to select a set of test cases the execution time of which remains within the limit but which is able to detect as many faults as possible. By now, this selection has been based on the subjective decision of the test laboratories.

My aim was to create a theoretical background to this test selection from an ATS. This kind of test selection was brought forward by practice and it is substantially different from the well-known test case generation methods ([Bosik91, Chow78, Dahbura90, Gonenc70, Sabnani88, Sarikaya82, Sidhu89, Sun97, Vuong92, Vuong97, Zhu97]). There does not exist a method by which we can select from an ATS so I had to create a formal model, which will be introduced in this thesis summary. Since the ATSs of the important protocols exist and they are standardized, I chose the ATSs as the basis of the selection model.

5 New results

5.1 Thesis I : Automation in the test selection problem: subpurposes, data elements, data levels

At the present, in the practice of conformance testing the only standardized notation is the Abstract Test Suite, which is given in a standardized structured test language, the TTCN (Tree and Tabular Combined Notation) ([ISO9646, Baum94, Sarikaya92, Probert92]). The main novelty in the method, which I propose hereafter, is that a widely usable and **automated method** can be worked out taking the ATS as a basis. **Let the input of the test selection method be the standardized ATS**. One of the advantages of the proposed method is that it takes such a description for a basis of test selection that always exists, while the existing test generation methods (DS, TT, UIO, W-method, see [Tarnay91, Dahbura90, Uyar98]) use the Finite State Machine (FSM) based descriptions (e.g.: SDL). An additional advantage of the method is that the standardized ATS contains the machine processable form of the TTCN (TTCN.MP) so the automation is easy. I proved my statements in [J3, C1, C3, C4, C5].

Thesis I.1 : Test purposes, definition of subpurposes

> I have defined the **subpurposes** as an **automatically detectable approximations** of the conformance requirements. The conformance requirements are identified with test purposes and summarized in a standardized test document. As these test documents are unsuitable for machine processing and one test purpose is related to more than one conformance requirement, I split the test purposes into subpurposes (Figure 1) in such a way that these subpurposes can be obtained automatically from the ATS.

The two main roles of conformance testing is to check the protocol dynamic behaviour and data handling. The data handling is described with sent and received data elements, while the dynamic behaviour is characterized with the behaviour tree of the protocol. The existing methods mainly focus on

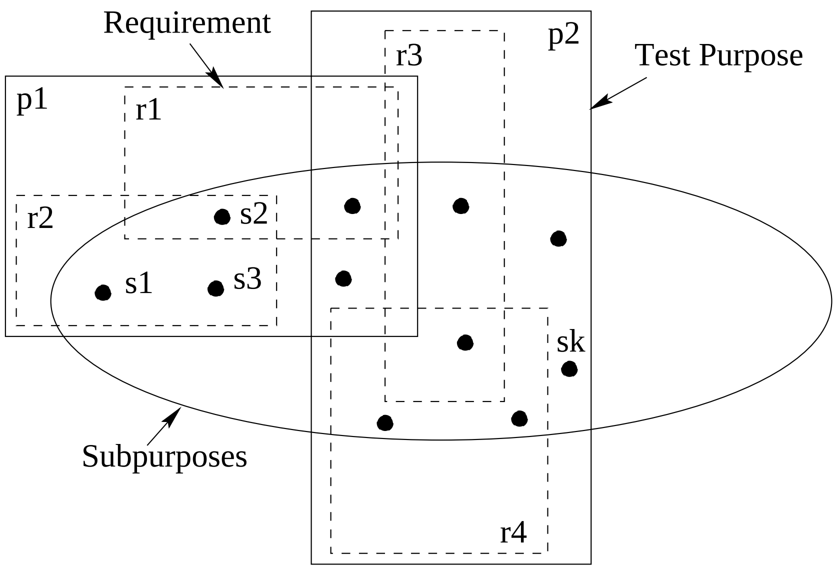

Figure 1: Requirements, test purposes, and subpurposes

the dynamic behaviour and the behaviour tree. In modern telecommunication protocols (e.g.: HTTP, WAP, etc.), however, the data flow play an increasingly significant role compared to the dynamic behaviour.

Standard [ISO9646] deals with specification of the test suite structure, test purposes and the coverage of the conformance requirements of the relevant protocol specification. The standard advises the test suite specifier to design the test suite structure and test purposes focusing on PDUs sent to or received from the IUT, on the values of individual parameters, etc.

Thesis I.2 : Using the data elements in test selection, identifying them with the subpurposes

Since during test suite specification the data elements play such a significant role I have extended the idea to the test selection problem and formally described the relation of data elements and subpurposes. In other words, I have proposed that **the selection model should include the data elements of the protocol** in addition to the dynamic behaviour so I have identified the data elements with the subpurposes.

Thesis I.3 : Definition of the abstract data levels

Since the structure of data elements can differ from in different test suites, I have **defined the abstract data levels**, which I have associated with subpurposes depending on the size and complexity of the protocol. I have defined the abstract data levels in the following way:

1. level of *data type,*
2. level of *data,*
3. level of *data parameter.*

If the abstract test suite is written in TTCN, then the data levels are the following:

1. ASP and/or PDU type level,
2. ASP and/or PDU constraint level,
3. parameters of ASPs and/or PDUs: simple types, structured types, etc.

Thesis I.4 : Mathematical model

I have proposed a new model for test selection which formulates the problem mathematically on the bases of the previously defined notions. This model enables us to use mathematical optimization methods to select the best test set. I have introduced the following **subpurpose-test case incidence matrix** as well as a **weight** and a **cost vector** as a basis of the model:

	c =	c(t1)	c(t2)	. . .	c(tn)
w =		t1	t2		tn
w(s1)	s1	1	0	. . .	1
w(s2)	s2	1	1	. . .	0
⋮	⋮	⋮	⋮	⋱	⋮
w(sk)	sk	0	1	. . .	1

subpurposes: $SP = \{s_1, \ldots, s_k\}$

test cases: $TS = \{t_1, \ldots, t_n\}$

cost of test t_j: $c(t_j)$
weight (importance) of subpurpose s_i: $w(s_i)$

In the matrix, the j^{th} element in the i^{th} row is 1, if and only if test case t_j is able to check subpurpose s_i, otherwise it is 0. In other words, if we cannot get any information about the subpurpose by executing the test case, then this element is 0. Hereafter, let us call the tests which can give information about the subpurpose *related to the subpurpose.*

In the selection model, the cost usually corresponds to time (seconds, minutes, etc.). The weight of the subpurposes represent the importance, which I classified by integer numbers from 1 to 10. Of course, other representation of the cost and weight vectors can be used too.

5.2 Thesis II : Coverage models and optimization problems

I have defined four coverage models with the help of the previously defined mathematical notations, then using these coverage models I have formulated two optimization problems in order to make a connection between the test selection problem and the theory of operational research. I presented my statements in [J3, C3, C4, C5].

Thesis II.1 : Coverage models:

During the selection, the "effectiveness" of the selected test set (let us denote it with T) have to be determined. For this purpose, I have proposed the following notions:

- the *cost of the selected test set* $c(T)$**:** sum of the costs of the selected test cases belonging to T,
- the *coverage of the selected test set* $cov(T)$**:** the weighted sum of the individual coverages of the subpurposes.

The *coverage of a subpurpose* is the proportion measuring how much of the protocol requirements represented by the subpurpose is checked by the selected test cases. Obviously, if all test cases related to a subpurpose are in the selected test set, then this proportion and the coverage is 1; if the selected test set does not contain any related test case, then it is 0. Between these two extreme values the coverage of the subpurpose depends only on the number of the related test cases in the selected test set. I have proposed four possible functions for the coverage, which had been worked out on the basis of practical experience:

1. **All or Nothing model:** The coverage of the subpurpose is 0 unless every related test case is selected.
2. **Step and Jump model:** Adding a new test case to the selected ones will increase the coverage of the subpurpose only by a relatively small amount until we reach the maximum number of the related test cases is reached.
3. **Linear model:** The coverage is in direct proportion to the number of selected tests: the more related test cases are selected, the bigger coverage is obtained.
4. **One is Enough model:** If at least one of the related test cases is selected, the whole coverage is obtained.

Figure 2 shows the coverage models presented above. The signs ($\circ$, $*$, $\times$, $\Box$) representing the individual coverage models show the coverage of an imaginary subpurpose as a function of the number of the selected, related test cases.

Thesis II.2 : Optimization problems

I have formulated the optimization problem in test selection as **two mathematical programming problems** using the above presented coverage models so I have made the known methods ([Nemhauser98, Wolsey98]) of operational research applicable to optimal test selection:

1. **Minimal cost problem**: Given a lower bound (K) for the coverage. Find the set of test cases that satisfies this bound with minimal cost:

$$\begin{array}{rl} \min & c(T) \\ \text{subject, to} & cov(T) \geq K \\ & T \subseteq TS \end{array}$$

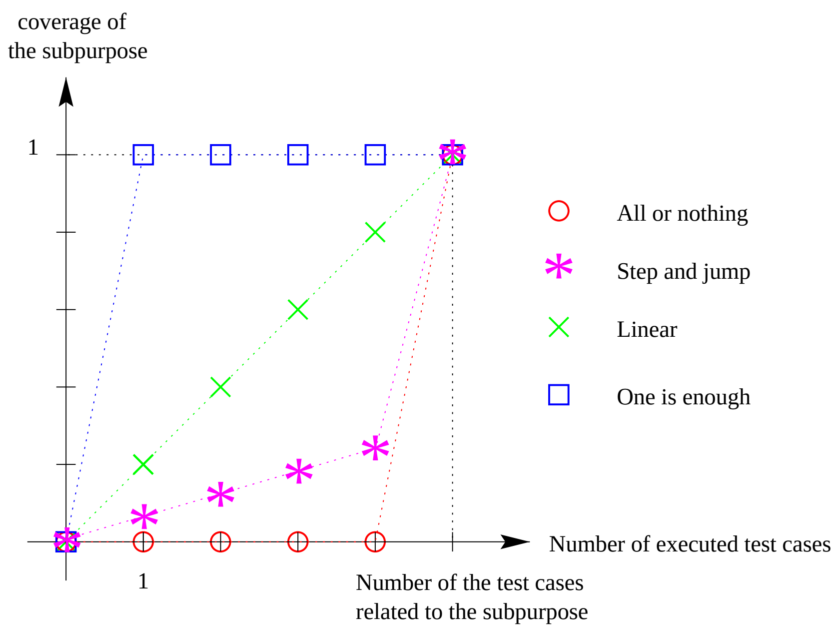

Figure 2: Coverage models

2. **Maximal coverage problem**: Given an upper bound (L) for the cost. Find the subset of test cases the cost of which is not more than L and checks as large part of the protocol (i.e.: has as big coverage) as possible:

$$\begin{aligned} \max \quad & cov(T) \\ \text{subject, to} \quad & c(T) \leq L \\ & T \subseteq TS \end{aligned}$$

5.3 Thesis III : Heuristic solution methods

The optimization problems outlined previously are NP-hard, so there is not known (and cannot be expected) an algorithm which is always able to solve the problem in polinomially bounded time. In [J3, J4, C3, C4, C5] with my colleague, Balázs Kotnyek, we formulated the test selection problem as an Integer Linear Programming (ILP) problem and solved it with commercial ILP solvers. Because of the complexity of the problem, the running time of the solvers can be unacceptably long, so we had to stop the algorithm after the time available has elapsed. This meant that we could not always get an optimal or even nearly optimal solution.

To get better solutions, I have proposed that heuristic algorithms should be used. There is another reason why heuristic methods were developed: commercial integer linear programming solvers are complicated and expensive. In addition, the methods used for determining the inputs (e.g.: the cost and weight vectors or the subpurpose-test case incidence matrix) of the test selection problem, by their nature, are based on estimations and "soft" considerations regarding the protocol. Hence, an exact optimal selection is only optimal up to these approximative inputs. This implies that the difference between the potentially inaccurate solution of a heuristic method and the exact optimum is only quantitative, not qualitative. Moreover, even a small quantitative difference is absolutely acceptable when considering the practice of testing.

I present the heuristic methods and algorithms to the minimal cost problem. The maximal coverage problem can be handled very similarly.

I have solved the test selection problem using the following well-known heuristic methods: Greedy algorithms, Tabu Search, Genetic Algorithms and Simulated Annealing. [J1] and [J2] contain the detailed heuristic algorithms for the test selection problem.

Thesis III.1 : Greedy algorithms

I have proposed four algorithms, which **select the executed test cases in a greedy way**. The first one (Algorithm ADD) adds the test case to the selected test set, which has minimal cost among the unselected ones, until the coverage bound is reached. The second one (Algorithm DROP) supposes that the selected test set contains every test case. Then in each step excludes the one with maximal cost, provided that it has not been examined before if the coverage is still above the upper bound.

The third (ADD-DELTA) and the fourth (DROP-DELTA) algorithms are more sophisticated greedy algorithms for the minimal cost problem. We first calculate the change in the coverage and the cost for every test case which is a candidate for adding or dropping. Then considering the ratio of these changes ($\frac{\Delta cost}{\Delta cov}$), we add or drop the test case to or from the set of selected test cases which implies the maximal increase in the coverage with minimal increase in cost. The DELTA in the names of the algorithms refers to these changes.

These algorithms are very fast but usually are not able to give acceptable solutions. Above these four algorithms I have proposed a fifth one (GREEDY) that will be a basic step in the further heuristics. Moreover, these simple algorithms can model the human or subjective test selection made by the testers in test laboratories, so they give a possibility for a comparative analysis with the more complex heuristic algorithms.

Thesis III.2 : Tabu Search

I have extended the Reactive Tabu Search algorithm ([Glover86, Glover89, Glover90, Pirlot96, Battiti94, Battiti96]) to the test selection problem by making these improvements:

- To make the algorithm faster, it is more efficient to evaluate only a previously determined subset of all the possible neighbours and find the best of this smaller subset instead of the whole neighbourhood. The neighbour where the algorithm will move to is randomly selected from the best members of the evaluated subset. The ratio of the evaluated neighbours depends on the number of the best members in the previous iterations. If there had been more bests in the recent iterations than required, then there is no need to evaluate as many neighbours, so by decreasing the ratio of the evaluated neighbours the algorithm can be made faster. On the other hand, if too few best members have been found among the evaluated ones, then the ratio should be increased to avoid trapping in a local optimum. I worked out the algorithm in such a way that the parameter determining the ratio of the evaluated neighbours is adapted to the state space of the problem (*adaptive neighbourhood sampling*). I have implemented the method and applied it to real-life applications.

Thesis III.3 : Genetic Algorithms

I have proposed a method on the basis of a generally known **Genetic Algorithm** ([Caprara98, Beasley96, Chu97]) for test selection problem with the following modifications:

- To **build the initial population** and **make the solutions feasible,** we use Algorithm GREEDY (Thesis III.1).
- To keep account of the population's diversity we determine **the number of mutated coordinates** (*mutrate*) based on the diversity of the population (*adaptive mutation rate*):

$$mutrate = \left\lfloor 1 + \frac{maxmut - 1}{popdiv + 1} \right\rceil;$$

$$popdiv = \left\lfloor \frac{popmax - popmin}{avrgcost} \right\rceil$$

where $maxmut$ is a user defined parameter specifying the maximal mutation rate allowed, $popmax = \max\{c(T) \mid t \in Population\}$ and $popmin = \min\{c(T) \mid t \in Population\}$ denote the highest and lowest cost in the population and $avrgcost = \frac{1}{n}\sum_{i=1}^{n} c(t_i)$ is the average cost of the test cases. $\lfloor a \rceil$ denotes the closest integer to a.

Figure 3 shows the mutation rate as the function of $popdiv$ with $maxmut = 10$. I chose a function which decreases from the $maxmut$ value very fast and gives 1 if the $popdiv$ value is high. I have tested the effect of the adaptive mutation rate on real-life applications.

Thesis III.4 : Simulated Annealing

I have applied the Simulated Annealing algorithm ([Pirlot96, Johnson89, Johnson91]) for the test selection problem by **introducing the following improvements**:

- To **find the initial feasible solution** I use Algorithm GREEDY (Thesis III.1).
- The set of the current solution's neighbours depends on the change in the cost in the previous iterations (*adaptive neighbourhood*

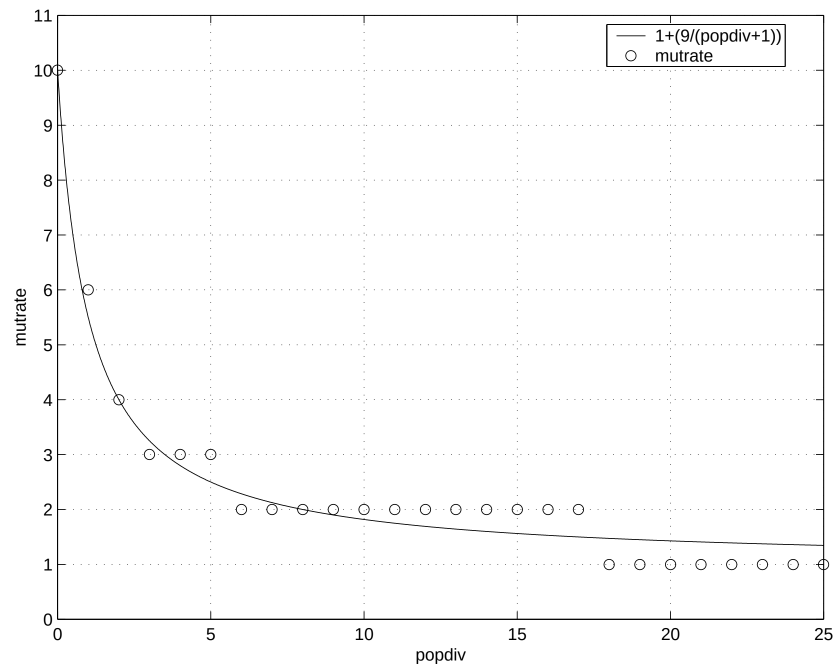

Figure 3: The adaptive variable mutation rate

search). In other words, the following formula determines the maximal number (*neighbour*) of coordinate values flipped :

$$neighbour = min\left\{maxneigh,\ \left\lfloor \frac{solvar}{3} + minneigh \right\rfloor\right\};$$

$$solvar = \left\lfloor \frac{|currsol - prevsol|}{avrgcost} \right\rceil$$

where $maxneigh$ and $minneigh$ are the maximal and minimal values allowed, $currsol = c(T_{cur})$ is the cost value of the current solution, $prevsol = c(T_{prev})$ is the cost value of a previous solution and $avrgcost$ is the average cost of the test cases defined in Thesis III.3. Furthermore, $\lfloor a \rfloor$ means the greatest integer number inferior to a, and $\lfloor a \rceil$ denotes the closest integer to a.

We can get better solutions using this function, because the algorithm is given larger freedom exploring several directions at the beginning of the search while at the end, the algorithm finds a suitable solution.

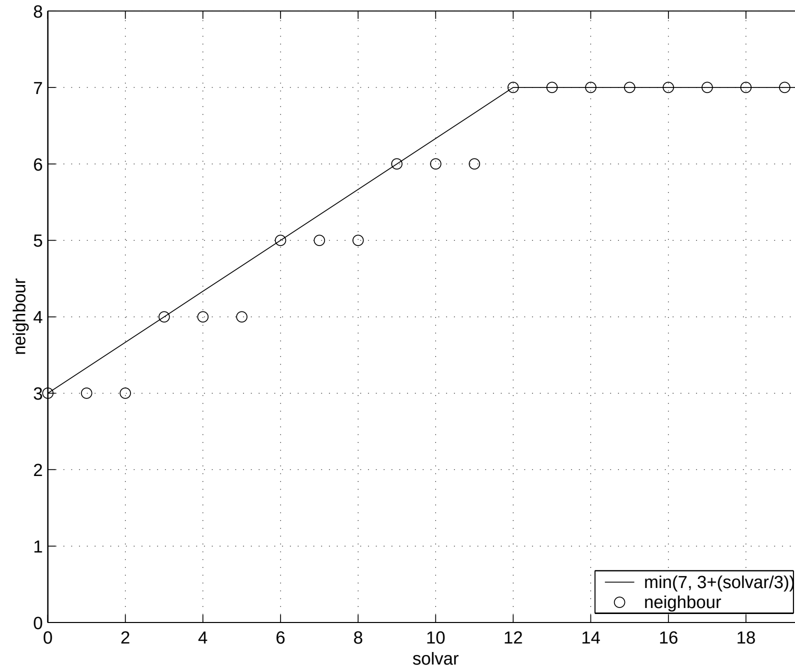

Figure 4: The adaptive variable neighbourhood structure

The values of *neighbour* for varying values of *solvar* in case of $maxneigh = 7$ and $minneigh = 3$ are shown in Figure 4. I have tested the adaptive neighbourhood search on real-life applications with different parameter settings.

Thesis III.5 : Cooling schedule in Simulated Annealing

The cooling schedule strongly influences the efficiency of the algorithm. It consists of setting the initial temperature ($Temp_1$) and the cooling factor (q) by which the temperature is decreased in each step. To find the best initial temperature and cooling factor I have performed empirical measurements with the following values:

$$Temp_1 = 2^{l-5} \text{ for } l = 1, \ldots, 15 \text{ and } q = 1 - 10^{-\frac{m}{3}} \text{ for } m = 1, \ldots, 15$$

and for all the 225 combinations I let the algorithm run 10 times. The number of runs seemed to be enough to draw conclusions, as the variances of the solutions were negligible. Using the empirical experiences, **I have introduced a function measuring the efficiency**

of the cooling schedule by taking into account both the achieved solution and the execution time. To this aim, let the efficiency be defined as the weighted sum of the standardized average solution and the standardized average execution time:

$$efficiency = \alpha_1 \frac{avrgsol - minsol}{maxsol - minsol} + \alpha_2 \frac{avrgtime - mintime}{maxtime - mintime},$$

where $avrgsol = \frac{1}{10}\sum_{i=1}^{10} c(T_i)$, $minsol = \min(c(T_i) \mid i = 1, \ldots, 10)$ and $maxsol = \max(c(T_i) \mid i = 1, \ldots, 10)$ are the average, minimum and maximum solution costs in the 10 trials. In the same way we get the $avrgtime = \frac{1}{10}\sum_{i=1}^{10} time_i$, $mintime = \min(time_i \mid i = 1, \ldots, 10)$ and $maxtime = \max(time_i \mid i = 1, \ldots, 10)$ values for the execution times of the algorithm.

The efficiency function and its projection for the 225 parameter settings with $\alpha_1 = \alpha_2 = 1$ are presented in Figure 5. The darker a region is in the projection, the more efficient is the cooling schedule. It seems that the algorithm is more sensitive for setting the initial temperature than cooling factor.

6 Application of the results

The established test suite optimization method is applicable to a wide area of practice because of the generic mathematical model. Therefore, the practical applicability of the selection method is not limited to conformance testing. The method is applicable to any kind of testing if the problem can be described mathematically in the same way. For example, the optimization model can be applied to test selection during test case generation.

There is another possibility to expand the application area by using the method for a selection problem arising in other testing methods (e.g.: function, negative, regression) instead of conformance testing. It is again required that the problem can be described mathematically in the same way as in case of conformance testing.

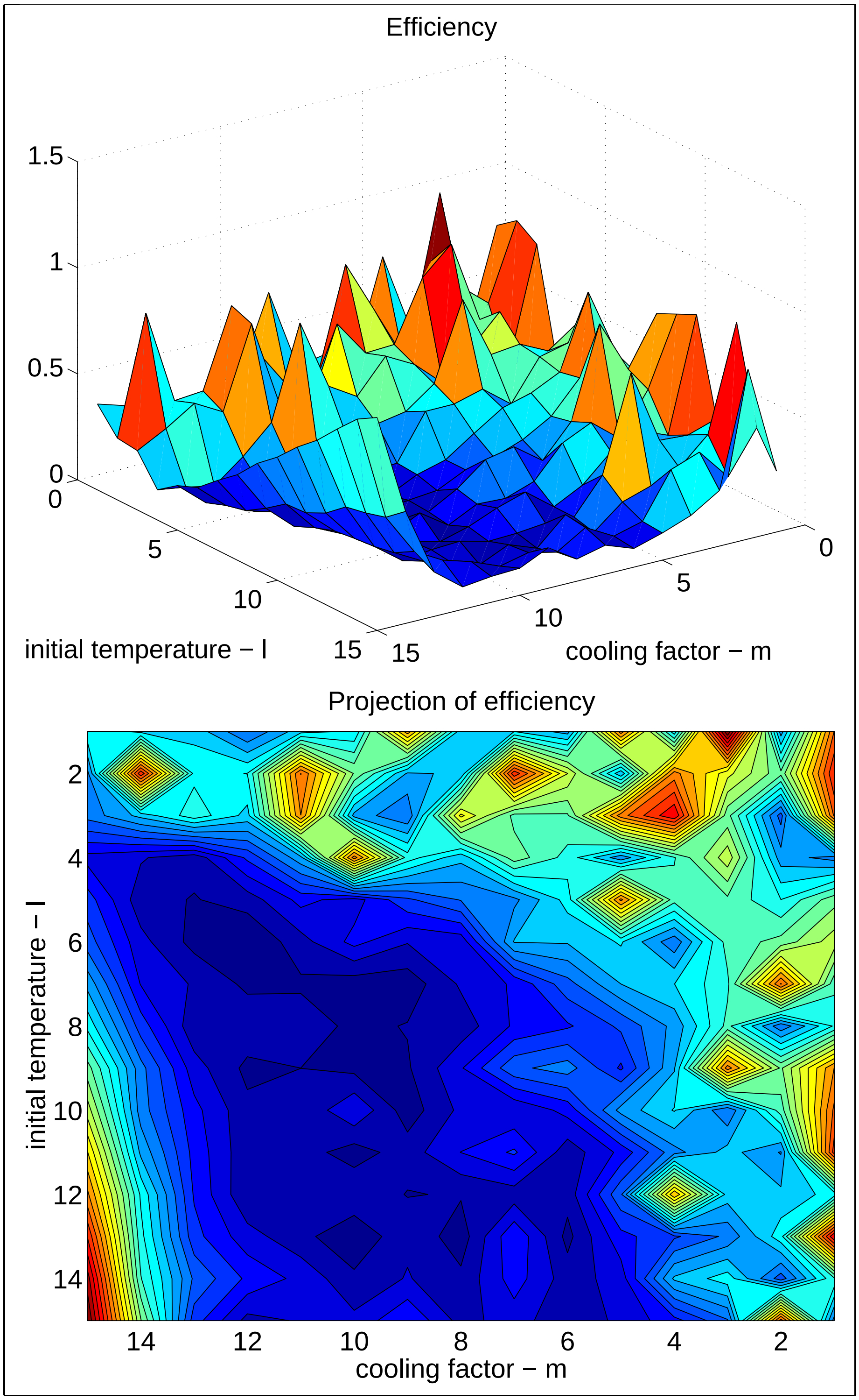

Figure 5: The efficiency function and its projection

A good example for this is the widely used function test method at Ericsson. With my colleagues, we applied the optimization method to “BGC Attendant ISDN-E Connection” function test suite ([BGC]).

The techniques that improved the performance of the heuristic algorithms can be applied to any kind of optimization problems so the presented ideas can be used in the theory of heuristic methods, offering a possibility of applying them in other disciplines.

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