

Evaluating LTL Satisfiability Solvers

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Abstract. We perform a comprehensive experimental evaluation of off-the-shelf solvers for satisfiability of propositional LTL. We consider a wide range of solvers implementing three major classes of algorithms: reduction to model checking, tableau-based approaches, and temporal resolution. Our set of benchmark families is significantly more comprehensive than those in previous studies. It takes the benchmark families of previous studies, which only have a limited overlap, and adds benchmark families not used for that purpose before.

We find that no solver dominates or solves all instances. Solvers focused on finding models and solvers using temporal resolution or fixed point computation show complementary strengths and weaknesses. This motivates and guides estimation of the potential of a portfolio solver. It turns out that even combining two solvers in a simple fashion significantly increases the share of solved instances while reducing CPU time spent.

1 Introduction

More and more, system specifications are not only used for classical verification of the correctness of a given system, e.g., via model checking, but they themselves become the subject of investigation (e.g., [56,33]). This is justified by observations in industry that many specifications contain errors (e.g., [16]) as well as by transition to property-based design (e.g., [57]). Propositional Linear Temporal Logic (LTL) [29] is a popular choice for system specifications and many checks on specifications reduce to determining (un)satisfiability (see, e.g., [56,33,60]). Hence, satisfiability of LTL is of considerable practical relevance.

A broad range of techniques for determining satisfiability of LTL has been developed: tableau-based methods (e.g., [68,48,63]), temporal resolution (e.g., [32]), and reduction to model checking (e.g., [60,69,25]). Despite the relevance of the problem and the range of techniques, we are not aware of a recent, comprehensive experimental comparison of solvers for satisfiability of propositional LTL on a broad set of benchmarks. In fact, the only line of work containing a representative from each of the above mentioned techniques that we know is the one by Hustadt et al. [45,42,46] (see below), which is somewhat dated.

In this paper we make the following contributions. 1. We perform an experimental evaluation of solvers for satisfiability of propositional LTL using ALASKA [1,69], LWB [2,41], NuSMV [3,26], `pltl` [4], TRP++ [5,44], and TSPASS [6,51]. Both the range of techniques in the solvers we use and the set of benchmarks we collected are significantly more comprehensive than in any previous study we know.

We have made our data available for further analysis [7]. 2. We consider number of solved instances, run time, memory usage, and model size. The analysis is greatly helped by using contour/discrete raw data plots, which complement the traditional cactus plots by preserving the relationship between benchmark instances. 3. The analysis shows complementary behavior between some solvers. This motivates estimating the potential of a portfolio solver. We consider portfolio solvers without communication between members of the portfolio for a best case scenario (which is unrealistic) and a reference case scenario (which any portfolio solver should aim to beat). Finally, we show that even a trivially implementable solver that sequentially executes one solver first for a short amount of time and, if necessary, then invokes another solver reduces the number of unsolved instances as well as the average run time.

Related Work Rozier and Vardi compare several explicit state and symbolic BDD-based model checkers for LTL satisfiability checking [60]. They find the symbolic tools to be superior in terms of performance and, generally, also in terms of quality. They do not consider SAT-based bounded model checkers, tableau-based solvers, or temporal resolution. While they perform an in-depth comparison of solvers using very similar techniques, our focus is on comparing selected representatives of a broad variety of techniques. We also use more benchmark families and consider memory usage and model size. The same authors compare symbolic constructions of Büchi automata in [59] using the BDD-based engine of *Cadence SMV* as backend solver. They show that a portfolio approach to automata construction is advantageous. De Wulf et al. compare *NuSMV* and *ALASKA* [69]. For a detailed discussion see Sect. 6. Hustadt et al. perform several comparisons [45,42,46] of *TRP*, a version of *LWB*, and a version of *SMV* on the *trp* benchmark set (see Sect. 4). Goré and Widmann perform an experimental comparison of solvers for CTL [37]. Goranko et al. [35] compare an implementation of Wolper’s tableau construction with *plt1*. For references on solver competitions and on their methodology see App. A of [62].

We are not aware of previous work on portfolio approaches to LTL satisfiability, except for [59]. We use entire solvers as members of a portfolio, while [59] uses different frontends for Büchi automata construction all relying on the same BDD-based backend solver. For other problem classes see, e.g., [43] (graph coloring, web browsing), [49] (winner determination problem), [34] (constraint satisfaction, mixed integer programming), [70] (SAT), or [58] (QBF).

Organization In Sect. 2 we introduce notation. In Sect. 3, 4, and 5 we describe solvers, benchmarks, and methodology. Section 6 contains the results of our evaluation. An estimation of the potential of a portfolio solver follows in Sect. 7. Section 8 concludes. Due to space constraints the following parts are in appendices [62]: general concepts and terminology (App. A), details on our benchmark set (App. B), discussion (App. C), and some plots (App. D).

2 Preliminaries

We consider formulas in future time propositional LTL with temporal operators **F**, **G**, **R**, **U**, **X**. We assume familiarity with LTL; otherwise see [29].

The terminology we use is largely standard (e.g., [64,19]); a reader unfamiliar with competition terminology is referred to App. A of [62]. A somewhat non-standard term we use is *configuration*, which denotes a tool (solver) with specific option values. A tool is a *state-of-the-art contributor* (sota) if an instance is solved only by configurations of that tool (see also [66]). Given a set of configurations C the *virtual best solver* (vbs) is the hypothetical solver using the best configuration in C on any given instance (e.g., [19]). We use **bold font** for sets of benchmark instances and **teletype** for configurations.

3 Solvers

Choice of Solvers We consider tools to solve satisfiability of propositional LTL from 3 major classes of approaches: 1. reduction to model checking, 2. tableau-based algorithms, and 3. temporal resolution. Tools were chosen as detailed below. To the best of our knowledge this set of solvers is the most diverse considered in an evaluation of solvers for satisfiability of propositional LTL to date.

Reduction to Model Checking We chose ALASKA [1,69] and NuSMV [3,26] using BDDs (NuSMV-BDD) and SAT (NuSMV-SBMC). We ruled out explicit state model checkers, as they did not scale as well as BDD-based symbolic model checkers for LTL satisfiability in [60]. The BDD-based engine of Cadence SMV [8] performed comparable to NuSMV-BDD in [60]. `sal-smc` [54] constructs explicit Büchi automata and was found not to scale [60]. The BDD-based variant of VIS [67] uses explicit construction of Büchi automata; initial experiments confirmed that this does not scale for satisfiability of LTL. `sal-bmc` [54] can only prove safety properties [53]. For an alternative using SAT-based symbolic model checking we contacted the VIS group for advice on recommended configurations (the space of configurations is quite large), but have not received an answer yet. Finally, we checked the publicly available versions of the participants of HWMCC’10 [20]; as far as we could see, the solvers that are not included in our study only handle safety properties.

Tableau-Based Algorithms We chose LWB [2,41] and `pltl` [4]. TWB [15] is superseded by `pltl` [36]. LTL Tableau turns out to be inferior to `pltl` [35].

Temporal Resolution We chose TRP++ [5,44] and TSPASS [6,51]. An alternative tool is TeMP [47]. TeMP was shown to be inferior to TRP++ on propositional problems in [47] and comparable to TSPASS on monodic problems in [51]. Note, that TSPASS is fair, while TeMP is not [50].

Solver Descriptions Below we briefly describe the tools we consider as well as the set of their options that we take into account. Note that not all combinations of options are valid. Due to space constraints the descriptions have to be kept short, and we refer the reader to the respective tool documentation.

ALASKA performs model checking and satisfiability checking of LTL via symbolic computation of fixed points using antichains [1,69]. Relevant options are: `noc/c` dis-/enables model construction, `nos/s` uses a semisymbolic/fully symbolic algorithm, and `nob/b` switches between forward and backward image computation. We use version 0.4 with an additional patch by N. Maquet.

LWB [2,41] implements tableau-based algorithms for LTL by Janssen [48] (no model construction) in the function “satisfiable” and by Schwendimann [63] (model construction) in the function “model”. Neither has relevant options. We designate the former by **sat** and the latter by **mod**. We use version 1.1.

NuSMV-BDD In this evaluation we treat NuSMV [3,26] as two tools NuSMV-BDD and NuSMV-SBMC. NuSMV-BDD performs symbolic model checking of LTL using symbolic fixed point computation with BDDs [27]. Experience with NuSMV-BDD allows us to restrict experiments to the following options. **nodcx/dcx** en-/disables model construction, **noflt/flt** dis-/enables forward computation of reachable states in the model and tableau for the LTL formula, **nodyn/dyn** dis-/enables dynamic reordering, and **elbwd/elfwd** switches between backward and forward image computation in the Emerson-Lei algorithm [30,40]. We use version 2.5.0.

NuSMV-SBMC performs incremental simple bounded model checking [39] of LTL using MiniSat [9]. Options considered are **nodcx/dcx** to en-/disable model construction and **noc/c** to dis-/enable checking completeness. With the latter disabled NuSMV-SBMC cannot solve *unsat* instances. We use version 2.5.0.

plt1 [4] implements tableau-based algorithms for LTL along the lines of [38] via the command line argument “graph” and by Schwendimann [63] via the command line argument “tree”. Neither has model construction or relevant options. We designate the former by **graph** and the latter by **tree**. We use version r1424.

TRP++ [5,44] uses temporal resolution for LTL [32]. Relevant options: **nos/s** to dis-/enable simplification, **nor/r** to dis-/enable rewriting, **noal/al** to ex-/include an order statement, **dfs/bfs** to choose dfs/bfs in loop search, **nop/p** to dis-/enable pre-test for sometime resolution, and **nofsr/fsr** to dis-/enable forward subsumption resolution. TRP++ cannot construct models. We use v. 2.x.

TSPASS [6,51] is a temporal resolution solver for monodic first-order temporal logic with model construction for propositional LTL [52]. We consider **noext/ext** to dis-/enable extended step clauses, **nogrp/grp** to dis-/enable regrouping of **X**, **nosev/sev** to dis-/enable transforming multiple eventualities into a single one, **log/sub** to select logical equivalence or subsumption in loop tests, **nosls/sls** to dis-/enable sequential loop search, **norfmrr/rfmrr** (resp. **norbmrr/rbmrr**) to dis-/enable forward (resp. backward) matching replacement resolution, **nomod/mod** to dis-/enable model construction, and **mur/mor** to select unordered or ordered resolution in model construction. We use version 0.94-0.16.

4 Benchmarks

In Tab. 1 we give an overview of the benchmark families we use. To our knowledge this set of benchmarks is the most comprehensive used for evaluating propositional LTL satisfiability solvers so far. [60] used **rozier_counter**, **rozier_pattern**, and **rozier_formulas**. [69] used **alaska_lift**, **alaska_szymanski**, and subsets of **rozier_counter** and **rozier_formulas**. [46] used **trp**. Note that there is little overlap. [60,69] and [46] represent separate communities. We added the following benchmark families that, to our knowledge,

family	max. size	num. sat	num. unsat	num. unkn.	source	description
application						
acacia_demo-v22	76	10	-	-	[10,31]	window screens
acacia_demo-v3	426	36	-	-	[10,31]	arbiters (scaled up, added variants)
acacia_example	144	25	-	-	[10,31]	mostly arbiters and traffic light controllers
alaska_lift	4450	102	34	-	[1,69]	lifts (scaled up, added variants, added fixes [61])
alaska_szymanski	183	4	-	-	[1,69]	mutual exclusion protocols
anzu_amba	6173	43	-	8	[11,23]	microcontroller buses (scaled up, added variants)
anzu_genbuf	5805	48	-	12	[11,24]	generalized buffers (scaled up, added variants)
forobots	636	14	25	-	[17]	foraging robots
crafted						
rozier_counter	751	78	-	-	[12,60]	serial counters (long models)
rozier_pattern	7992	244	-	-	[12,60]	patterns to test explicit state model checkers (scaled up)
schuppan_O1formula	4007	-	27	-	(new)	patterns that trigger exponential behavior in some solvers
schuppan_O2formula	6001	-	15	12		
schuppan_phltl	40501	-	10	8	(new)	temporal formulation of pigeonhole principle [22]
random						
rozier_formulas	185	1943	57	-	[12,60]	random formulas as in [28] (subset of original family)
trp	1422	573	397	-	[13,46]	random formulas from fixed conjunctive normal form templates (subset of original family)

Table 1. Overview of benchmark families, grouped by benchmark categories. The first column lists the name of the family. Columns 2 – 5 show the size (see App. A of [62]) of the largest instance and the number of *sat*, *unsat*, and *unknown* instances, respectively, in that family. The 6th column provides references to the source and the 7th column gives a brief description.

had not been used to evaluate solvers for propositional LTL satisfiability before: **acacia**, **anzu**, and **forobots**.³ To provide more challenging instances we scaled up some families. Moreover, for the families **acacia_demo-v3**, **anzu_amba**, and **anzu_genbuf**, which consist of a set of assumptions and a set of guarantees, we not only used the form $(\bigwedge_i a_i) \rightarrow (\bigwedge_i g_i)$ but also $(\bigwedge_i a_i) \wedge (\bigwedge_i g_i)$ (marked by “c” in the family name). For **acacia_demo-v3**, **alaska_lift**, **anzu_amba**, and **anzu_genbuf** we added variants with liveness conditions to trigger nontrivial behavior (marked by “l” in the family name). For **alaska_lift** we also use a fixed [61] variant (marked by “f” in the family name). Finally, we added the families **schuppan_O1formula**, **schuppan_O2formula**, and **schuppan_phltl**. Our set of benchmarks contains 3723 instances. All benchmarks are available from [7].

5 Methodology

Hardware and Software We used machines with Intel Xeon 3.0 GHz processors and 4 GB memory running Red Hat Linux 5.4 with 64 bit kernel 2.6.18-164.2.1.el5. Run time and memory usage were measured with `run` [21].

Input Format and No Shuffling We converted all instances into NuSMV format and from there to the input formats of the other tools. We did not syntactically alter instances as there was no risk of cheating by syntactic recognition of benchmarks (e.g., [18]) and we, too, think that syntactic information should be preserved for the benefit of solvers (e.g., [64]).

Stages The valid option combinations of the options in Sect. 3 yield the following number of configurations (model construction dis-/enabled): ALASKA 4/2, LWB 1/1, NuSMV-BDD 6/4, NuSMV-SBMC 2/2, p1t1 2/-, TRP++ 64/-, TSPASS 128/128.

³ While the full version of [59] uses **acacia** and **anzu**, these were included based on a previous submission of this paper that we made available to the authors of [59].

The number of configurations of TRP++ and TSPASS is too large to include all of them in the main stage of our evaluation. We therefore performed a preliminary stage with a time limit of 10 seconds and a memory limit of 2 GB on a representative subset of instances. In that stage we used all 64 combinations of TRP++. For TSPASS we considered the following subset of configurations: all options at their default value (sometimes implied by other options) as well as a single option switched to its non-default value. This resulted in 24/24 configurations. We then fixed options that either had a clear benefit one way or the other or clearly had little effect to the corresponding values and kept the remaining configurations for the main stage (see Sect. 6). In the main stage all configurations of ALASKA, LWB, NuSMV-BDD, NuSMV-SBMC, and plt1 as well as the remaining configurations of TRP++ and TSPASS were run with a time limit of 60 seconds and a memory limit of 2 GB.

In each stage, each configuration was run only once on each instance. While performing more than one run would provide more accurate information about run time distributions [55] performing only a single run allows to use more configurations, more instances, or higher time bounds with equal resources.

Tracks We have two tracks: one for configurations with model construction disabled (e.g., LWB using `mod` constructs models but is superior to `sat` that doesn't) and one for configurations with model construction enabled. The former considers all instances; the latter is restricted to *sat* instances.

Correctness of Solvers is a recurring issue in tool competitions and comparisons (e.g., [60]). Besides obvious cross checking of the *sat/unsat* results reported by different configurations for the same instance we used the fact that NuSMV-SBMC produces shortest (possibly plus one) models as an additional correctness check. We did not perform further validation of generated models.

Scoring We essentially use scoring based on a higher number of solved instances and lower time taken on solved instances (see Sect. 2) as it preserves and clearly shows what we consider two important performance indicators.

However, there are fairly big differences in the number of instances in our benchmark families. Still, we would like to consider many benchmarks rather than only sampling the larger families. Hence, we modify the above scoring method as follows. We consider the benchmark families as a tree. We then compute the share of solved instances and the average run time on solved instances for each leaf (here all instances have equal weight). Then, for each non-leaf node, aggregate values are computed as averages with equal weights for all children of that node. For the tree of families see App. B.2 of [62].

6 Results

For more plots and data see App. D of the full version [62] and the website [7].

Preliminary Stage For TRP++ configurations with `s_nor` proved inferior so that only `s_r`, `nos_r`, and `nos_nor` were kept. The effects of `noal/al`, `dfs/bfs`, and `nofsr/fsr` are unclear; hence all combinations were kept. `nop/p` had little effect so that we set it to its default `nop`. All in all this left us with 24 configurations.

tool	model construction dis- or enabled (all instances)				model construction enabled (<i>sat</i> instances)			
	winning configuration	max	min	vbs	winning configuration	max	min	vbs
ALASKA	noc_nos_nob	0.581	0.322	0.595	c_nos_nob	0.595	0.318	0.595
LWB	mod	0.740	0.656	0.800	mod	0.795	0.795	0.795
NuSMV-BDD	dcx_fflt_dyn_elbwd	0.743	0.607	0.823	nodcx_fflt_dyn_elbwd	0.754	0.625	0.771
NuSMV-SBMC	nodcx_c	0.723	0.651	0.726	nodcx_noc	0.860	0.857	0.861
pltl	tree	0.694	0.687	0.702	—	—	—	—
TRP++	s_r_noal_bfs_nop_fsr	0.752	0.593	0.776	—	—	—	—
TSPASS	ext_nogrp_nosev_sub_nosls_rfmrr_norbarr_nomod_mor	0.667	0.479	0.670	ext_grp_sev_sub_nosls_rfmrr_rbarr_mod_mor	0.531	0.495	0.538

Table 2. Selecting a winning configuration per tool (separately for tracks). The left-most column lists the tool name. Next come 2 groups of 4 columns. The 1st group is for configurations with model construction dis- or enabled, the 2nd with model construction enabled. In each group the 1st column shows the winning configuration per tool. The 2nd column shows its score, the 3rd column shows the worst score, and the 4th column shows the score of the vbs of all configurations of that tool.

For TSPASS `ext`, `nosev`, `sub`, and `mor` turned out to be advantageous. The effects of `nogrp/grp`, `norfmrr/rfmrr`, and `norbarr/rbarr` are unclear and we kept all. `nosls/sls` had little effect so that we disabled it as is default. This resulted in 8 configurations each with model construction disabled and enabled.

We now move to the main stage.

Correctness of Solvers We found no bug in `pltl` but 1 or 2 bugs in each of NuSMV, ALASKA, TRP++, and TSPASS. All of them were kindly fixed by the respective tool authors. As of now we are not aware of wrong results or bugs triggered in the above tools by our benchmark set. In LWB we found several bugs. We emailed our findings to the developers but have not received a response. There are currently 187 out of 7446 (non-negated and negated) instances known to us that trigger bugs in LWB; 13 are wrong results. Hence, LWB is hors-concours. Some large instances failed in ALASKA and TSPASS due to certain built-in limits. These instances were rerun with increased limits.

Selecting Winning Configurations per Tool To focus the subsequent comparison we select one winning configuration per tool to be used for the comparisons between tools in the remainder of this section. We choose the configuration with the highest weighted share of solved instances (see Sect. 5) for each tool. We distinguish between model construction dis- or enabled and model construction enabled as model construction is not available for some tools or options.

Table 2 provides a summary. For all tools except NuSMV-BDD and LWB the weighted share of instances solved by the winning configurations is close to that of the vbs of all configurations of that tool (Tab. 2). Below we mostly restrict the analysis to the winning configurations. We use the tool name to identify the respective winning configurations.

Track Model Construction Disabled In Fig. 1 we show *contour/discrete raw data plots* of the run time for the winning configurations with model construction dis- or enabled. The name is taken from [65]. A somewhat related way to display results of a solver competition was used in Pseudo-Boolean Competitions [14].

Contrary to cactus plots *contour/discrete raw data plots* retain the relationship between instances (one x-coordinate corresponds to the same rather than different instances) but are more legible than line plots. They allow to see the performance of the solvers on benchmark families that are a subfamily of the one comprising a plot. A particular advantage is that they permit identification of similar and complementary behavior in performance. They also allow to see

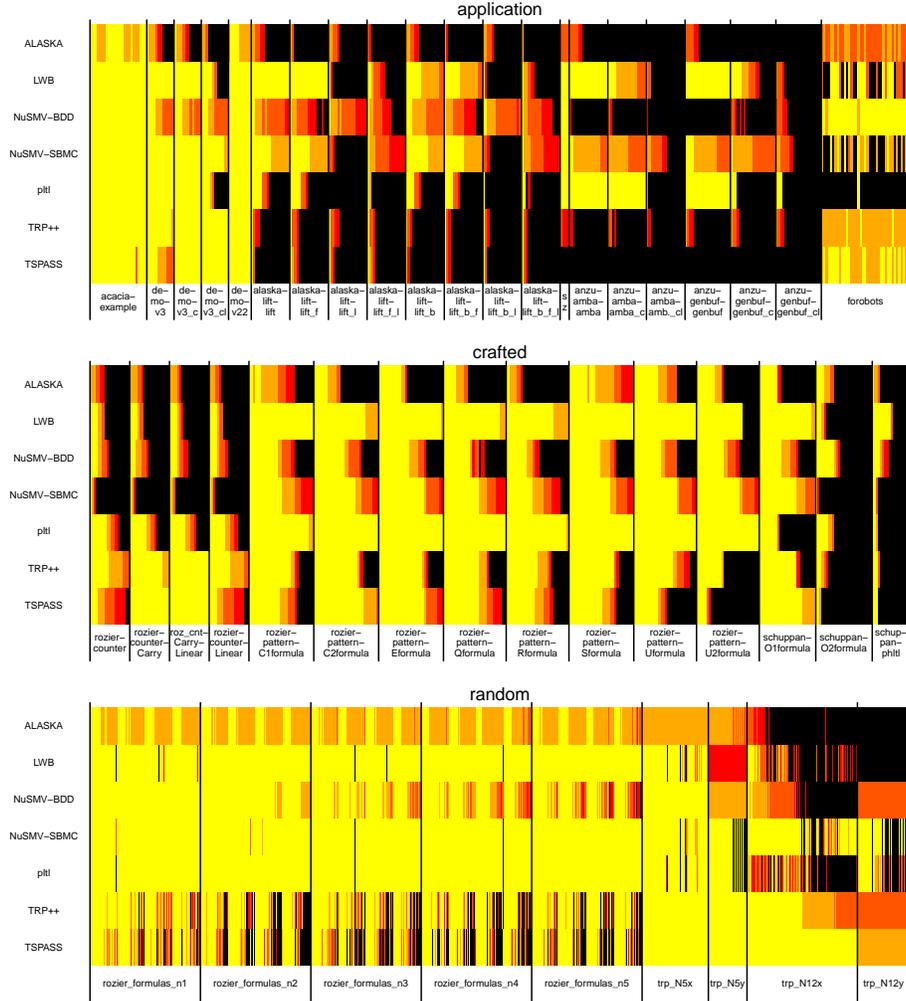


Fig. 1. Contour/discrete raw data plots of run time for winning configurations with model construction dis- or enabled (all instances). Instances are on the x-axes (only identified by their families), configurations on the y-axes. Each rectangle represents the run time of one configuration on one instance. **sz** abbreviates **alaska_szymanski**, **roz_cnt** abbreviates **rozier_counter**, and **demo** stands for **acacia_demo**. Run times are encoded using the following colors: ■ ≤ 0.1 sec; ■ > 0.1 sec, ≤ 1 sec; ■ > 1 sec, ≤ 10 sec; ■ > 10 sec, ≤ 60 sec; ■ unsolved.

how difficult a particular instance or subfamily is. However, these plots make it harder to determine a ranking of solvers by higher number of solved instances with ties broken by lower average time taken on solved instances. Due to space constraints we cannot show both kinds of plots for the same data. We chose to use the contour/discrete raw data plots here to demonstrate their utility. For corresponding cactus plots see Fig. 10–13 in App. D.2 of [62].

Overall Picture In this paragraph we refer to all configurations used in the main stage. No configuration solves all instances. 8–12 instances in **anzu_amba**,

anzu_genbuf, **schuppan_O2formula**, and **schuppan_phltl** remain unsolved. The instances in the former two families are expected to be *sat*, in the latter *unsat*. The smallest unsolved instance is **O2formula50** (size 301). NuSMV-BDD is a sota on a number of (*unsat*) instances in **alaska_lift** and **schuppan_O2formula**; NuSMV-SBMC on instances in **alaska_lift**, **anzu_amba**, and **anzu_genbuf** (all *sat*); TRP++ on instances in **rozier_counter** (*sat*); LWB on instances in **schuppan_phltl** (*unsat*). See also Fig. 8 in App. D.1 of [62].

Families The majority of benchmark families contain instances that are challenging for some solver. In category **application** the 3 families with larger instances, **alaska_lift**, **anzu_amba**, and **anzu_genbuf**, are the more difficult ones. Among them the variants that were modified to trigger meaningful behavior are the hardest. In category **crafted** the (*unsat*) families **schuppan_O2formula** and **schuppan_phltl** are the most difficult. **rozier_counter** is hard for most solvers, except for TRP++ and TSPASS (and NuSMV-BDD in a configuration using only backward fixed point computation). The two families in category **random** show very different pictures. Family **rozier_random** is solved well by non-resolution-based tools but somewhat more difficult for TRP++ and TSPASS; roles are reversed in family **trp**. Note that **trp** comes from the temporal resolution community, while **rozier_random** is taken from the model checking community.

Solvers: Similarities and Differences Figure 1 shows that TRP++ and TSPASS, which both use temporal resolution, have similar strengths and weaknesses. TSPASS tends to improve over TRP++ on **trp**, while TRP++ tends to be faster on most of the remaining families. Between the two tools using symbolic fixed point computation NuSMV-BDD mostly dominates ALASKA; the latter has a higher start up time than the other tools. The strengths and weaknesses of NuSMV-BDD mostly resemble those of TRP++ and TSPASS. Intuitively, symbolic fixed point computation [30] is closer in spirit to temporal resolution as performed in TRP++ [44] than to searching models (stating a more formal relationship is left as future work). LWB, NuSMV-SBMC, and **pltl** display similar characteristics. Note that these solvers essentially try to find models, although NuSMV-SBMC uses a fairly different technique than **pltl** and LWB. It is important to note that the strengths and weaknesses of NuSMV-BDD, TRP++, and TSPASS are somewhat complementary to those of LWB, NuSMV-SBMC, and **pltl**.

Sat versus Unsat Instances NuSMV-SBMC exhibits the largest difference in its behavior between *sat* and *unsat* instances. NuSMV-SBMC solves most *sat* instances among the solvers. A notable exception is **rozier_counter**, which has shortest models of exponential size; few shortest models outside **rozier_counter** have size larger than 3 (see below). On the contrary, NuSMV-BDD and ALASKA, which are based on symbolic fixed computation, are hardly affected. For plots see Fig. 14–17 in App. D.3 of [62] and Fig. 18–21 in App. D.4 of [62].

Instance Size The two tools based on symbolic fixed point computation, ALASKA and NuSMV-BDD, show a fairly clear influence of the size of an instance on their run time. At the other end of the spectrum are LWB and **pltl**, trying to find models. They solve some large instances in almost no time. For plots see Fig. 22–25 in App. D.5 of [62].

Non-negated versus Negated Instances The relevance of negated versions of instances is questionable. We have not included negated versions of instances in any part of this paper, except where stated explicitly. However, we briefly comment on one aspect because of the size of the observed effect. On the **rozier_formulas** family — where negation should not change any relevant characteristic of the benchmark set — the variation in performance between the non-negated and the negated version of an instance is considerably higher for TSPASS and TRP++ than for NuSMV-BDD and ALASKA. For scatter plots see Fig. 26 in App. D.6 of [62].

Memory Memory usage turned out to be less of a problem than time taken, therefore we do not report detailed results. In fact, very rarely a configuration used more than 300 MB when it solved an instance. ALASKA typically used most memory. For plots see App. D of [62].

VBS rather than Winning Configurations While the findings above were mostly stated for the winning configurations of each tool, the picture does not change significantly when comparing the vbs of each tool (for plots see App. D of [62]). As suggested by Tab. 2 notable improvements only happen for NuSMV-BDD, LWB, and, to a lesser extent, TRP++.

Track Model Construction Enabled We focus on model size. Figure 2 shows a cactus plot for the winning configurations with model construction enabled (*sat* instances). A vbs of all configurations with model construction enabled solves all but the largest instances of **anzu_amba**, **anzu_genbuf**, and **rozier_counter**. NuSMV-BDD is a sota based on instances in **rozier_counter**; NuSMV-SBMC on instances in **alaska_lift**, **anzu_amba**, **anzu_genbuf**, and **rozier_pattern**; LWB on instances in **rozier_pattern**.

95 % of the satisfiable instances have shortest models of size 3 or less. Instances with shortest models of size larger than 11 are either from **rozier_counter** or from the variants in **application** modified to trigger meaningful behavior.

NuSMV-SBMC mostly produces shortest models, while NuSMV-BDD produces the longest ones. On the other hand, NuSMV-BDD solves more instances of the **rozier_counter** family (which has very long models) than the other tools.

A Performance Advantage of ALASKA over NuSMV-BDD? In [69] De Wulf et al. perform a comparison between ALASKA and NuSMV-BDD for satisfiability and model checking of LTL. For LTL satisfiability they find that ALASKA outperforms NuSMV-BDD on **alaska_lift**, **alaska_szymanski**, and a subfamily of **rozier_formulas**, while NuSMV-BDD performs better on **rozier_counter**.

A comparison of the antichain-based algorithm in ALASKA [69] and the Emerson-Lei algorithm [30] used in NuSMV-BDD shows that the algorithm in [69] computes fixed points using forward image computation, while NuSMV-BDD up to version 2.4.3 only uses (as is common) backward image computations for [30]. This triggered us to implement a forward version (e.g., [40]) of the Emerson-Lei algorithm in NuSMV-BDD. Figure 3 shows that the forward version performs considerably better than the backward version on the **rozier_formulas** family. Using forward image computation NuSMV-BDD outperforms ALASKA on

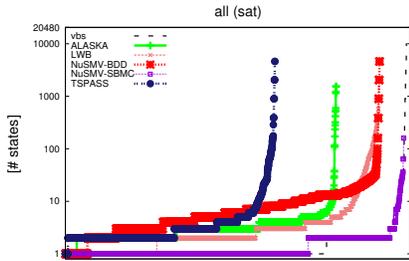


Fig. 2. Cactus plot of model size for the winning configurations with model construction enabled (*sat* instances).

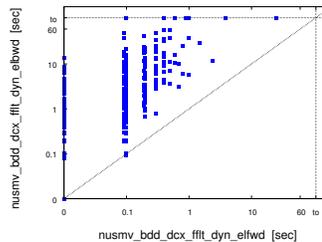


Fig. 3. Scatter plot comparing run time for the forward and the backward version of the Emerson-Lei algorithm in NuSMV-BDD on the *rozier_formulas* family. “to” marks *time-out*.

rozier_formulas. Note also that ALASKA can be switched to perform backward image computation in which case its performance degrades considerably.

Our evaluation shows that NuSMV-BDD can solve the *alaska_lift* and *alaska_szymanski* families easily (and faster than ALASKA) by restricting computation to reachable states (*fflt*) and enabling dynamic reordering (*dyn*).

7 Potential of a Portfolio Solver

In the previous section we saw that some configurations behave complementarily. This motivates constructing *portfolio solvers* that consist of a set of configurations with the goal that the resulting solver performs better than any of its constituent configurations (e.g., [43]). Different modes of execution are considered for portfolio solvers in the literature (e.g., [43,49,34,70]).

Perfect Oracle We assume an oracle that for each instance predicts (using no time and memory) an optimal configuration in a portfolio and then executes that configuration on that instance (see, e.g., [49]). I.e., the performance of a portfolio solver on an instance is determined by the performance of an optimal configuration in a portfolio on that instance. If configurations do not collaborate (e.g., by exchanging partial results) that is a bound on the performance of a practical solver using that portfolio. An alternative view of this mode of execution is that each member of the portfolio is run on a separate processor in parallel until one configuration finishes while taking into account only the cost of one processor and disregarding the cost of other processors.

We estimate the potential of such a portfolio solver by considering all portfolios consisting of subsets of winning configurations with model construction disabled from Tab. 2. Figure 4 shows the result.

While individual configurations solve at most a weighted share of 0.752, using a portfolio helps to solve up to 0.931. All portfolios that solve a weighted share of 0.866 or more contain at least one of ALASKA, NuSMV-BDD, TRP++, and TSPASS and at least one of LWB, NuSMV-SBMC, and *plt1*. All that solve 0.9 or more contain at least one of LWB and NuSMV-SBMC and at least one of TRP++ and TSPASS. The 4 best portfolios with two configurations are (LWB, TRP++), (LWB, TSPASS), (NuSMV-SBMC, TRP++), and (NuSMV-SBMC, TSPASS). Adding ALASKA to a portfolio that contains NuSMV-BDD does not help in most cases.

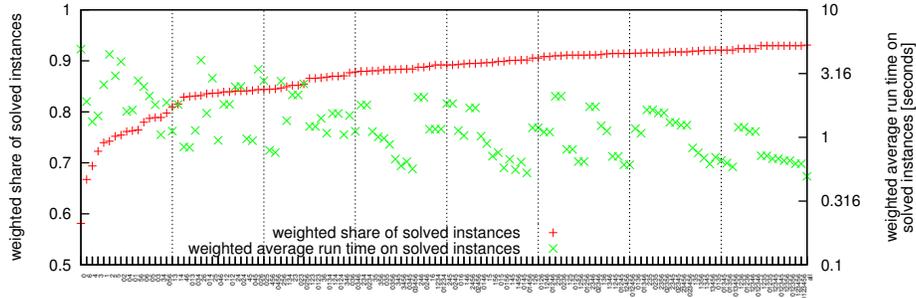


Fig. 4. Potential of a portfolio solver consisting of subsets of the winning configurations with model construction dis- or enabled using a perfect oracle. Portfolios are identified by their constituent configurations: 0: ALASKA; 1: LWB; 2: NuSMV-BDD; 3: NuSMV-SBMC; 4: p1t1; 5: TRP++; 6: TSPASS. On the x-axis are the portfolios sorted in increasing order of weighted share of solved instances; ties are broken by decreasing order of weighted average run time on solved instances. For each portfolio the weighted share of solved instances is marked by a red vertical/horizontal cross (scale on the left y-axis); the corresponding weighted average run time on solved instances is marked by a green diagonal cross (scale on the right y-axis). “all” considers all configurations with model construction dis- or enabled rather than only the winning configurations. For an enlarged plot see App. D.8 of [62].

Perfect Task Switcher We now assume that all configurations of a portfolio are executed on a single processor in a time-sharing fashion with equal and infinitely small time slices, no task switching overhead, and memory usage not an issue (e.g., [43]). I.e., rather than assuming a perfect oracle, we only assume a perfect task switcher. Now the performance of a portfolio solver with k configurations on an instance is determined by the performance of an optimal configuration in a portfolio on that instance multiplied by k (that might induce *time-out* even if some configuration solves the instance). If configurations do not collaborate this can be considered a portfolio solver that any practical portfolio solver using that portfolio should aim to beat. An alternative view is that each portfolio member runs on a separate processor in parallel until one member finishes and taking into account the cost for all processors.

For a plot analogous to Figure 4 see App. D.8 of [62]. Here the best portfolio considered is (LWB, NuSMV-BDD, NuSMV-SBMC, TRP++), which solves a weighted share of 0.922. Otherwise, similar remarks as for the case of a perfect oracle apply.

Fast Presolver We now show that even a simplistic portfolio solver (implementable as shell script) can yield considerable benefits. We take the 4 best 2-configuration portfolios from above and use one of the two solvers as *fast presolver* [70] by executing it until it either solves an instance or reaches its (short) time limit. If the instance is not yet solved, then we execute the other solver for the remaining time (60 seconds minus the time limit of the presolver).

Results are shown in Tab. 3. In each case the portfolios using a fast presolver significantly increase the weighted share of solved instances while decreasing the weighted average run time over the respective portfolio members in isolation.

8 Conclusion

Benchmarks and data from our evaluation, available at [7], identify reference solvers with their command line options at the level of benchmark instances.

	1st in isolation		2nd in isolation		perfect oracle		perf. task switcher		1st as fast presolver		2nd as fast presolver					
	share time	share time	share time	share time	share time	share time	share time	share time	1 second	2 seconds	1 second	2 seconds				
(LWB, TRP++)	0.740	2.59	0.752	3.03	0.896	0.89	0.894	1.12	0.880	1.09	0.885	1.30	0.841	1.26	0.850	1.45
(LWB, TSPASS)	0.740	2.59	0.667	1.91	0.889	1.16	0.881	1.27	0.868	0.88	0.874	1.10	0.850	1.20	0.858	1.48
(NuSMV-SBMC, TRP++)	0.723	1.47	0.752	3.03	0.880	1.11	0.874	1.37	0.823	1.03	0.841	1.18	0.860	0.97	0.862	1.31
(NuSMV-SBMC, TSPASS)	0.723	1.47	0.667	1.91	0.867	1.41	0.853	1.60	0.813	1.00	0.831	1.21	0.837	1.17	0.840	1.42

Table 3. Performance of the 4 best 2-configuration portfolios in various execution modes. After the portfolio members in the 1st column there are 8 groups of 2 columns. In each group the 1st column shows the weighted share of solved instances, the 2nd column shows the weighted average run time on solved instances in seconds. The 1st and 2nd column groups are for the 1st and 2nd member of each portfolio in isolation. The 3rd and 4th groups are for perfect oracle and perfect task switcher modes. The 5th and 6th groups are for fast presolver mode with 1 and 2 seconds time limit when the 1st member of the portfolio is used as a fast presolver; the 7th and 8th groups are analogous for the 2nd member as a fast presolver. The time limits of 1 and 2 seconds were chosen among some that we tried as they represent a sweet spot that exhibits both an increase in weighted share of solved instances and a decrease in weighted average run time on solved instances.

This helps to improve existing solvers, provides a point of reference in the evaluation of new techniques, and can serve as a basis for developing heuristics for portfolio solvers. Our evaluation shows that solvers have different, complementary strengths and weaknesses. We do not declare any solver to be the winner (those who disagree are referred to Tab. 2). Instead, for a solver aiming to be competitive on a broad range of benchmarks we advocate a portfolio approach.

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