

The algorithm selection competitions 2015 and 2017 [☆]

Marius Lindauer ^{a,*}, Jan N. van Rijn ^b, Lars Kotthoff ^c

^a University of Freiburg, Germany

^b Columbia University, USA

^c University of Wyoming, USA

ARTICLE INFO

Article history:

Received 2 May 2018

Received in revised form 14 September 2018

Accepted 14 October 2018

Available online 4 January 2019

Keywords:

Algorithm Selection

Meta-Learning

Competition Analysis

ABSTRACT

The algorithm selection problem is to choose the most suitable algorithm for solving a given problem instance. It leverages the complementarity between different approaches that is present in many areas of AI. We report on the state of the art in algorithm selection, as defined by the Algorithm Selection competitions in 2015 and 2017. The results of these competitions show how the state of the art improved over the years. We show that although performance in some cases is very good, there is still room for improvement in other cases. Finally, we provide insights into why some scenarios are hard, and pose challenges to the community on how to advance the current state of the art.

© 2018 Elsevier B.V. All rights reserved.

1. Introduction

In many areas of AI, there are different algorithms to solve the same type of problem. Often, these algorithms are complementary in the sense that one algorithm works well when others fail and vice versa. For example in propositional satisfiability solving (SAT), there are complete tree-based solvers aimed at structured, industrial-like problems, and local search solvers aimed at randomly generated problems. In many practical cases, the performance difference between algorithms can be very large, for example as shown by Xu et al. [59] for SAT. Unfortunately, the correct selection of an algorithm is not always as easy as described above and even easy decisions require substantial expert knowledge about algorithms and the problem instances at hand.

Per-instance algorithm selection [45] is a way to leverage this complementarity between different algorithms. Instead of running a single algorithm, a portfolio [24,15] consisting of several complementary algorithms is employed together with a learned selector. The selector automatically chooses the best algorithm from the portfolio for each instance to be solved.

Formally, the task is to select the best algorithm A from a portfolio of algorithms \mathcal{P} for a given instance i from a set of instances \mathcal{I} with respect to a performance metric $m : \mathcal{P} \times \mathcal{I} \rightarrow \mathbb{R}$ (e.g., runtime, error, solution quality or accuracy). To this end, an algorithm selection system learns a mapping from an instance to a selected algorithm $s : \mathcal{I} \rightarrow \mathcal{P}$ such that the performance, measured as cost, across all instances \mathcal{I} is minimized (w.l.o.g.):

$$\arg \min_s \sum_{i \in \mathcal{I}} m(s(i), i) \quad (1)$$

[☆] This paper was submitted to the Competition Section of the journal.

* Corresponding author.

E-mail addresses: lindauer@cs.uni-freiburg.de (M. Lindauer), j.n.vanrijn@columbia.edu (J.N. van Rijn), larsko@uwyo.edu (L. Kotthoff).

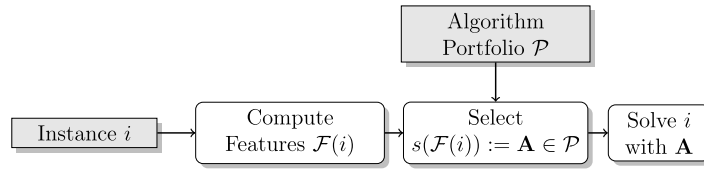


Fig. 1. Per-instance algorithm selection workflow for a given instance.

Algorithm selection has gained prominence in many areas and made tremendous progress in recent years. Algorithm selection systems established new state-of-the-art performance in several areas of AI, for example propositional satisfiability solving [57],¹ machine learning [5,54], maximum satisfiability solving [2], answer set programming [39,6], constraint programming [25,1], and the traveling salesperson problem [36]. However, the multitude of different approaches and application domains makes it difficult to compare different algorithm selection systems, which presented users with a very practical meta-algorithm selection problem – which algorithm selection system should be used for a given task. The algorithm selection competitions can help users to make the decision which system and approach to use, based on a fair comparison across a diverse range of different domains.

The first step towards being able to perform such comparisons was the introduction of the Algorithm Selection Benchmark Library (ASlib, [4]). ASlib consists of many algorithm selection scenarios for which performance data of all algorithms on all instances is available. These scenarios allow for fair and reproducible comparisons of different algorithm selection systems. ASlib enabled the competitions we report on here.

Structure of the paper. In this competition report, we summarize the results and insights gained by running two algorithm selection competitions based on ASlib. These competitions were organized in 2015 – *the ICON Challenge on Algorithm Selection* – and in 2017 – *the Open Algorithm Selection Challenge*.² We start by giving a brief background on algorithm selection (Section 2) and an overview on how we designed both competitions (Section 3). Afterwards we present the results of both competitions (Section 4) and discuss the insights obtained and open challenges in the field of algorithm selection, identified through the competitions (Section 5).

2. Background on algorithm selection

In this section, we discuss the importance of algorithm selection, several classes of algorithm selection methods and ways to evaluate algorithm selection problems.

2.1. Importance of algorithm selection

The impact of algorithm selection in several AI fields is best illustrated by the performance of such approaches in AI competitions. One of the first well-known algorithm selection systems was SATzilla [57], which won several first places in the SAT competition 2009 and the SAT challenge 2012. To refocus on core SAT solvers, portfolio solvers (including algorithm selection systems) were banned from the SAT competition for several years—now, they are allowed in a special track. In the answer set competition 2011, the algorithm selection system claspfolio [21] won the NP-track and later in 2015, ME-ASP [44] won the competition. In constraint programming, sunny-cp [1] won the open track of the MiniZinc Challenge for several years (2015, 2016 & 2017). In AI planning, a simple static portfolio of planners (fast downward stone soup; [19]) won a track at the International Planning Competition (IPC) in 2011. More recently, the online algorithm selection system Delfi [29] won a first place at IPC 2018. In QBF, an algorithm selection system called QBF Portfolio [22] won third place at the prenex track of QBFEVAL 2018.

Algorithm selection does not only perform well for combinatorial problems, but it is also an important component in automated machine learning (AutoML) systems. For example, the AutoML system auto-sklearn uses algorithm selection to initialize its hyperparameter optimization [14] and won two AutoML challenges [12].

There are also applications of algorithm selection in non-AI domains, e.g. diagnosis [30], databases [11], and network design [47].

2.2. Algorithm selection approaches

Fig. 1 shows a basic per-instance algorithm selection framework that is used in practice. A basic approach involves (i) representing a given instance i with a vector of numerical features $\mathcal{F}(i)$ (e.g., number of variables and constraints of a CSP

¹ In propositional satisfiability solving (SAT), algorithm selection systems were even banned from the SAT competition for some years, but are allowed in a special track now.

² This paper builds upon individual short papers for each competition [35,40] and presents a unified view with a discussion of the setups, results and lessons learned.

instance), (ii) inducing a selection machine learning model s that selects an algorithm for the given instance i based on its features $\mathcal{F}(i)$. Generally, these machine learning models are induced based on a dataset $\mathcal{D} = \{(\mathbf{x}_j, y_j) \mid j = 1, \dots, n\}$ with n datapoints to map an input \mathbf{x} to output $f(\mathbf{x})$, which closely represents y . In this setting, \mathbf{x}_i is typically the vector of numerical features $\mathcal{F}(i)$ from some instance i that has been observed before. There are various variations for representing the y values and ways for algorithm selection system s to leverage the predictions $f(\mathbf{x})$. We briefly review several classes of solutions.

Regression that models the performance of individual algorithms in the portfolio. A regression model $f_{\mathbf{A}}$ can be trained for each $\mathbf{A} \in \mathcal{P}$ on \mathcal{D} with $\mathbf{x}_j = \mathcal{F}(i)$ and $y_j = m(\mathbf{A}, i)$ for each previously observed instance i that \mathbf{A} was ran on. The machine learning algorithm can then predict how well algorithm \mathbf{A} performs on a given instance from \mathcal{I} . The algorithm with the best predicted performance is selected for solving the instance (e.g., [23,57]).

Combinations of unsupervised clustering and classification that partitions instances into clusters H based on the instance features $\mathcal{F}(i)$, and determines the best algorithm \mathbf{A}_i for each cluster $h_i \in H$. Given a new instance i' , the instance features $\mathcal{F}(i')$ determine the nearest cluster h' w.r.t. some distance metric; the algorithm \mathbf{A}' assigned to h' is applied (e.g., [3]).

Pairwise classification that considers pairs of algorithms $(\mathbf{A}_k, \mathbf{A}_j)$. For a new instance, the machine-learning-induced model predicts for each pair of algorithms which one will perform better ($m(\mathbf{A}_k, i) < m(\mathbf{A}_j, i)$), and the algorithm with most “is better” predictions is selected (e.g., [58,53]).

Stacking of several approaches that combine multiple models to predict the algorithm to choose, for example by predicting the performance of each portfolio algorithm through regression models and combining these predictions through a classification model (e.g., [31,46,43]).

2.3. Why is algorithm selection more than traditional machine learning?

In contrast to typical machine learning tasks, each instance has a weight attached to it. It is not be important to select the best algorithm on instances on which all algorithms perform nearly equally, but it is crucial to select the best algorithm on an instance on which all but one algorithm perform poorly (e.g., all but one time out). The potential gain from making the best decision can be seen as a weight for that particular instance.

Instead of predicting a single algorithm, schedules of algorithms can also be used. One variant of algorithm schedules [28,20] are static (instance-independent) pre-solving schedules which are applied before any instance features are computed [57]. Computing the best-performing schedule is usually an NP-hard problem. Alternatively, a sequence of algorithms can be predicted for instance-specific schedules [1,37].

Computing instance features can come with a large amount of overhead, and if the objective is to minimize runtime, this overhead should be minimized. For example, on industrial-like SAT instances, computing some instance features can take more than half of the total time budget.

For more details on algorithm selection systems and the different approaches used in the literature, we refer the interested reader to the surveys by Smith-Miles [48] and Kotthoff [33].

2.4. Evaluation of algorithm selection systems

The purpose of performing algorithm selection is to achieve performance better than any individual algorithm could. In many cases, overhead through the computation of the instance features used as input for the machine learning models is incurred. This diminishes performance gains achieved through selecting good algorithms and has to be taken into account for evaluating algorithm selection systems.

To be able to assess the performance gain of algorithm selection systems, two baselines are commonly compared against [59,38,2]: (i) the performance of the individual algorithm performing best on all training instances (called *single best solver* (SBS)), which denotes what can be achieved without algorithm selection; (ii) the performance of the *virtual best solver* (VBS) (also called oracle performance), which makes perfect decisions and chooses the best-performing algorithm on each instance without any overhead. The VBS corresponds to the overhead-free parallel portfolio that runs all algorithms in parallel and terminates as soon as the first algorithm finishes.

The performance of the baselines and of any algorithm selection system varies for different scenarios. We normalize the performance $m_s = \sum_{i \in \mathcal{I}} m(s(i), i)$ of an algorithm selection system s on a given scenario by the performance of the SBS and VBS, as a cost to be minimized, and measure how much of the gap between the two it closed as follows:

$$\hat{m}_s = \frac{m_s - m_{VBS}}{m_{SBS} - m_{VBS}} \quad (2)$$

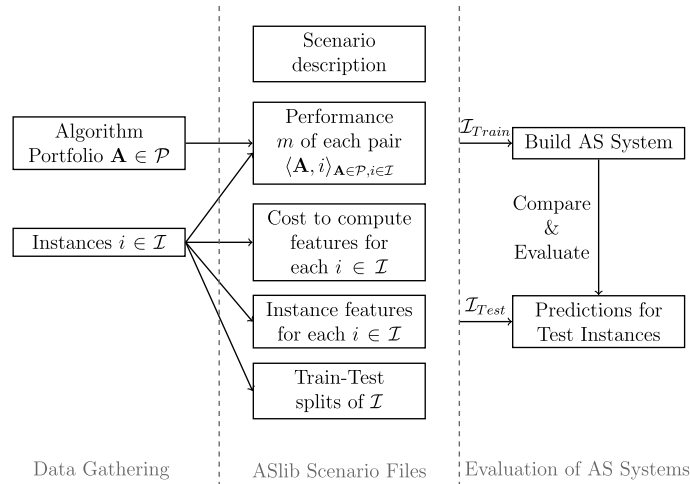


Fig. 2. Illustration of ASlib.

where 0 corresponds to perfect performance, equivalent to the VBS, and 1 corresponds to the performance of the SBS.³ The performance of an algorithm selection system will usually be between 0 and 1; if it is larger than 1 it means that simply always selecting the SBS is a better strategy.

A common way of measuring runtime performance is penalized average runtime (PAR10) [27,38,2]: the average runtime across all instances, where algorithms are run with a timeout and penalized with a runtime ten times the timeout if they do not complete within the time limit.

3. Competition setups

In this section, we discuss the setups of both competitions. Both competitions were based on ASlib, with submissions required to read the ASlib format as input.

3.1. General setup: ASlib

Fig. 2 shows the general structure of an ASlib *scenario* [4]. ASlib scenarios contain pre-computed performance values $m(\mathbf{A}, i)$ for all algorithms in a portfolio $\mathbf{A} \in \mathcal{P}$ on a set of training instances $i \in \mathcal{I}$ (e.g., runtime for SAT instances or accuracy for Machine Learning datasets). In addition, a set of pre-computed instance features $\mathcal{F}(i)$ are available for each instance, as well as the time required to compute the feature values (the overhead). The corresponding task description provides further information, e.g., runtime cutoff, grouping of features, performance metric (runtime or solution quality) and indicates whether the performance metric is to be maximized or minimized. Finally, it contains a file describing the train-test splits. This file specifies which instances should be used for training the system (\mathcal{I}_{Train}), and which should be used for evaluating the system (\mathcal{I}_{Test}).

3.2. Competition 2015

In 2015, the competition asked for complete systems to be submitted which would be trained and evaluated by the organizers. This way, the general applicability of submissions was emphasized – rather than doing well only with specific models and after manual tweaks, submissions had to demonstrate that they can be used off-the-shelf to produce algorithm selection models with good performance. For this reason, submissions were required to be open source or free for academic use.

The scenarios used in 2015 are shown in Table 1. The competition used existing ASlib scenarios that were known to the participants beforehand. There was no secret test data in 2015; however, the splits into training and testing data were not known to participants. We note that these are all runtime scenarios, reflecting what was available in ASlib at the time.

Submissions were allowed to specify the feature groups and a single pre-solver for each ASlib scenario (a statically-defined algorithm to be run before any feature computation to avoid overheads on easy instances), and required to produce a list of the algorithms to run for each instance (each with an associated timeout). The training time for a submission was limited to 12 CPU hours on each scenario; each submission had the same computational resources available and was

³ In the 2017 competition, the gap was defined such that 1 corresponded to VBS and 0 to SBS. For consistency with the 2015 results, we use the metric as defined in Equation (2) here.

Table 1

Overview of algorithm selection scenarios used in 2015, showing the number of algorithms $|A|$, the number of instances $|Z|$, the number of instance features $|F|$, the performance objective, and the improvement factor of the virtual best solver (VBS) over the single best solver (m_{SBS}/m_{VBS}) without considering instances on which all algorithms timed out.

Scenario	$ A $	$ Z $	$ F $	Obj.	Factor
ASP-POTASSCO	11	1294	138	Time	25
CSP-2010	2	2024	17	Time	10
MAXSAT12-PMS	6	876	37	Time	53
CPMP-2013	4	527	22	Time	31
PROTEUS-2014	22	4021	198	Time	413
QBF-2011	5	1368	46	Time	96
SAT11-HAND	15	296	115	Time	37
SAT11-INDU	18	300	115	Time	22
SAT11-RAND	9	600	115	Time	66
SAT12-ALL	31	1614	115	Time	30
SAT12-HAND	31	1167	138	Time	35
SAT12-INDU	31	767	138	Time	15
SAT12-RAND	31	1167	138	Time	12

executed on the same hardware. AutoFolio was the only submission that used the full 12 hours. The submissions were evaluated on 10 different train-test splits, to reduce the potential influence of randomness. We considered the three metrics mean PAR10 score, mean misclassification penalty (the additional time that was required to solve an instance compared to the best algorithm on that instance), and number of instances solved within the timeout. The final score was the average remaining gap \hat{m} (Equation (2)) across these three metrics, the 10 train-test splits, and the scenarios.

3.3. Competition 2017

Compared to 2015, we changed the setup of the competition in 2017 with the following goals in mind:

1. fewer restrictions on the submissions regarding computational resources and licensing;
2. better scaling of the organizational overhead to more submissions, in particular not having to run each submission manually;
3. more flexible schedules for computing features and running algorithms; and
4. a more diverse set of algorithm selection scenarios, including new scenarios.

To achieve the first and second goal, the participants did not submit their systems directly, but only the predictions made by their system for new test instances (using a single train-test split). Thus, also submissions from closed-source systems were possible, although all participants made their submissions open-source in the end. We provided full information, including algorithms' performances, for a set of training instances, but only the feature values for the test instances to submitters. Participants could invest as many computational resources as they wanted to compute their predictions. While this may give an advantage to participants who have access to large amounts of computational resources, such a competition is typically won through better ideas and not through better computational resources. To facilitate easy submission of results, we did not run multiple train-test splits as in 2015. We briefly investigated the effects of this in Section 5.4. We note that this setup is quite common in other machine learning competitions, e.g., the Kaggle competitions [9].

To support more complex algorithm selection approaches, the submitted predictions were allowed to be an arbitrary sequence of algorithms with timeouts and interleaved feature computations. Thus, any combination of these two components was possible (e.g., complex pre-solving schedules with interleaved feature computation). Complex pre-solving schedules were used by most submissions for scenarios with runtime as performance metric.

We collected several new algorithm selection benchmarks from different domains; 8 out of the 11 used scenarios were completely new and not disclosed to participants before the competition (see Table 2). We obfuscated the instance and algorithm names such that the participants were not able to easily recognize existing scenarios.

To show the impact of algorithm selection on the state of the art in different domains, we focused the search for new scenarios on recent competitions for CSP, MAXSAT, MIP, QBF, and SAT. Additionally, we developed an open-source Python tool that connects to OpenML [56] and converts a Machine Learning study into an ASlib scenario.⁴ To ensure diversity of the scenarios with respect to the application domains, we selected at most two scenarios from each domain to avoid any bias introduced by focusing on a single domain. In the 2015 competition, most of the scenarios came from SAT, which skewed the evaluation in favor of that. Finally, we also considered scenarios with solution quality as performance metric (instead of runtime) for the first time. The new scenarios were added to ASlib after the competition; thus the competition was not only enabled by ASlib, but furthers its expansion.

For a detailed description of the competition setup in 2017, we refer the interested reader to [40].

⁴ See <https://github.com/openml/openml-aslib>.

Table 2

Overview of algorithm selection scenarios used in 2017, showing the alias in the competition, the number of algorithms $|A|$, the number of instances $|I|$, the number of instance features $|F|$, the performance objective, and the improvement factor of the virtual best solver (VBS) over the single best solver (m_{SBS}/m_{VBS}) without considering instances on which all algorithms timed out. Scenarios marked with an asterisk were available in ASlib before the competition.

Scenario	Alias	$ A $	$ I $	$ F $	Obj.	Factor
BNSL-2016*	Bado	8	1179	86	Time	41
CSP-Minizinc-Obj-2016	Camilla	8	100	95	Quality	1.7
CSP-Minizinc-Time-2016	Caren	8	100	95	Time	61
MAXSAT-PMS-2016	Magnus	19	601	37	Time	25
MAXSAT-WPMS-2016	Monty	18	630	37	Time	16
MIP-2016	Mira	5	218	143	Time	11
OPENML-WEKA-2017	Oberon	30	105	103	Quality	1.02
QBF-2016	Qill	24	825	46	Time	265
SAT12-ALL*	Svea	31	1614	115	Time	30
SAT03-16_INDUI	Sora	10	2000	483	Time	13
TTP-2016*	Titus	22	9720	50	Quality	1.04

Table 3

Results in 2015 with some system running out of competition (ooc). The average gap is aggregated across all scenarios according to Equation (2).

Rank	System	Avg. gap	
		All	PAR10
1st	zilla	0.366	0.344
2nd	zillafolio	0.370	0.341
ooc	AutoFolio-48	0.375	0.334
3rd	AutoFolio	0.390	0.341
ooc	LLAMA-regrPairs ..	0.395	0.375
4th	ASAP_RF	0.416	0.377
5th	ASAP_kNN	0.423	0.387
ooc	LLAMA-regr	0.425	0.407
6th	flexfolio-schedules	0.442	0.395
7th	sunny	0.482	0.461
8th	sunny-presolv	0.484	0.467

4. Results

We now discuss the results of both competitions.

4.1. Competition 2015

The competition received a total of 8 submissions from 4 different groups of researchers comprising 15 people. Participants were based in 4 different countries on 2 continents. Appendix A provides an overview of all submissions.

Table 3 shows the final ranking. The zilla system is the overall winner, although the first- and second-placed entries are very close. All systems perform well on average, closing more than half of the gap between virtual and single best solver. Additionally, we show the normalized PAR10 score for comparison to the 2017 results, where only the PAR10 metric was used. Detailed results of all metrics (PAR10, misclassification penalty, and solved) are presented in Appendix D.

For comparison, we show three additional systems. Autofolio-48 is identical to Autofolio (a submitted algorithm selector that searches over different selection approaches and their hyperparameter settings [38]), but was allowed 48 hours training time (four times the default) to assess the impact of additional tuning of hyperparameters. LLAMA-regrPairs and LLAMA-regr are simple approaches based on the LLAMA algorithm selection toolkit [32].⁵ The relatively small difference between AutoFolio and AutoFolio-48 shows that allowing more training time does not increase performance significantly. The good ranking of the two simple LLAMA models shows that reasonable performance can be achieved even with simple off-the-shelf approaches without customization or tuning. Fig. 3 (combined scores) and Fig. 4 (PAR10 scores) show critical distance plots on the average ranks of the submissions. According to the Friedman test with post-hoc Nemenyi test, there is no statistically significant difference between any of the submissions.

More detailed results can be found in [34].

⁵ Both LLAMA approaches use regression models to predict the performance of each algorithm individually and for each pair of algorithms to predict their performance difference. Both approaches did not use pre-solvers and feature selection, both selected only a single algorithm, and their hyperparameters were not tuned.

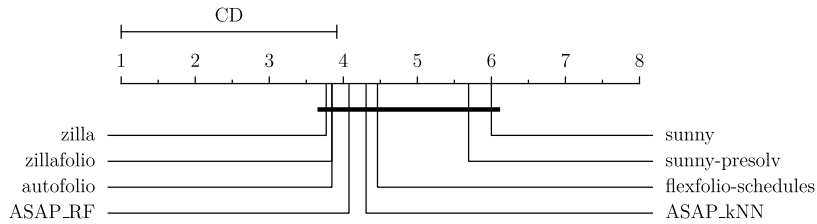


Fig. 3. Critical distance plots with Nemenyi Test on the 'All' scores (average across normalized scores based on PAR10, misclassification penalty, and number of solved instances) of the participants of the 2015 competition. If two submissions are connected by a thick line, there was not enough statistical evidence that their performances are significantly different.

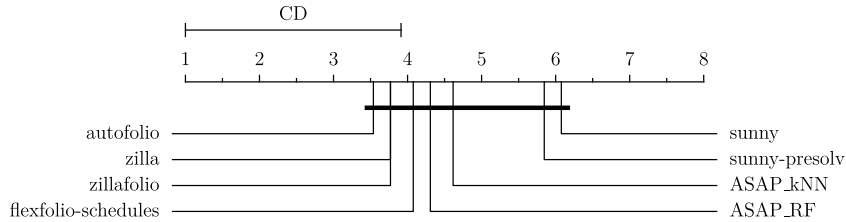


Fig. 4. Critical distance plots with Nemenyi Test on the PAR10 scores of the participants of the 2015 competition.

Table 4

Results in 2017 with some system running out of competition (ooc). The average gap is aggregated across all scenarios according to Equation (2).

Rank	System	Avg. gap	Avg. rank
1st	ASAP.v2	0.38	2.6
2nd	ASAP.v3	0.40	2.8
3rd	Sunny-fkvar	0.43	2.7
4th	Sunny-autok	0.57	3.9
ooc	*Zilla(fixed version)	0.57	N/A
5th	*Zilla	0.93	5.3
6th	*Zilla(dyn)	0.96	5.4
7th	AS-RF	2.10	6.1
8th	AS-ASL	2.51	7.2

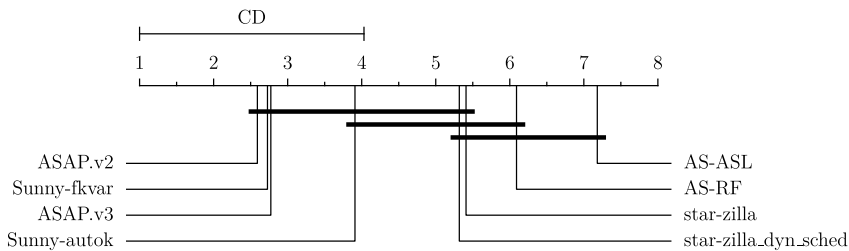


Fig. 5. Critical distance plots with Nemenyi Test on the PAR10 scores of the participants in 2017.

4.2. Competition 2017

In 2017, there were 8 submissions from 4 groups. Similar to 2015, participants were based in 4 different countries on 2 continents. While most of the submissions came from participants of the 2015 competition, there were also submissions by researchers who did not participate in 2015.

Table 4 shows the results in terms of the gap metric (see Equation (2)) based on PAR10, as well as the ranks; detailed results are in Table E.9 (Appendix E). The competition was won by ASAP.v2, which obtained the highest scores on the gap metric both in terms of the average over all datasets, and the average rank across all scenarios. Both ASAP systems clearly outperformed all other participants on the quality scenarios. However, Sunny-fkvar did best on the runtime scenarios, followed by ASAP.v2.

Fig. 5 shows critical distance plots on the average ranks of the submissions. There is no statistically significant difference between the best six submissions, but the difference to the worst submissions is statistically significant.

5. Open challenges and insights

In this section, we discuss insights and open challenges indicated by the results of the competitions.

5.1. Progress from 2015 to 2017

The progress of algorithm selection as a field from 2015 to 2017 seems to be rather small. In terms of the remaining gap between virtual best and single best solver, the results were nearly the same (the best system in 2015 achieved about 33% in terms of PAR10, and the best system in 2017 about 38%). On the only scenario used in both competitions (SAT12-ALL), the performance stayed nearly constant. Nevertheless, the competition in 2017 was more challenging because of the new and more diverse scenarios. While the community succeeded in coming up with more challenging problems, there appears to be room for more innovative solutions.

5.2. Statistical significance

Figs. 3, 4 and 5 show ranked plots, with the critical distance required according to the Friedman with post-hoc Nemenyi test to assert statistical significant difference between multiple systems [10]. In the 2015 competition, none of the differences between the submitted systems were statistical significant, whereas in the 2017 competition only some differences were statistical significant.

Failure to detect a significant difference does not imply that there is no such difference: the statistical tests are based on a relatively low number of samples and thus have limited power.

Even though the statistical significance results should be interpreted with care, the critical difference plots are still informative. They show, e.g., that the systems submitted in the 2015 challenge were closer together (ranked approximately between 3.5 and 6) than the systems submitted in 2017 (ranked approximately between 2.5 and 7).

5.3. Robustness of algorithm selection systems

As the results of both competitions show, choosing one of the state-of-the-art algorithm selection systems is still a much better choice than simply always using the single best algorithm. However, as different algorithm selection systems have different strengths, we are now confronted with a meta-algorithm selection problem – selecting the best algorithm selection approach for the task at hand. For example, while the best submission in 2017 achieved 38% gap between SBS and VBS remaining, the virtual best selector over the portfolio of all submissions would have achieved 29%. An open challenge is to develop such a meta-algorithm selection system, or a single algorithm selection system that performs well across a wide range of scenarios.

One step in this direction is the per-scenario customization of the systems, e.g., by using hyperparameter optimization methods [17,41,8], per-scenario model selection [42], or even per-scenario selection of the general approach combined with hyperparameter optimization [38]. However, as the results show, more fine-tuning of an algorithm selection system does not always result in a better-performing system. In 2015, giving much more time to Autofolio resulted in only a very minor performance improvement, and in 2017 ASAP.v2 performed better than its refined successor ASAP.v3.

In addition to the general observations above, we note the following points regarding robustness of the submissions:

- zilla performed very well on SAT scenarios (average rank: 1.4) but only mediocre on other domains (average rank: 6.5 out of 8 submissions) in 2015;
- ASAP won in 2017, but sunny-fkvar performed better on runtime scenarios;
- both CSP scenarios in 2017 were very similar (same algorithm portfolio, same instances, same instance features) but the performance metric was changed (one scenario with runtime and one scenario with solution quality). On the runtime scenario, Sunny-fkvar performed very well, but on the quality scenario ASAP.v3/2 performed much better.

5.4. Impact of randomness

One of the main differences between the 2015 and 2017 challenges was that in 2015, the submissions were evaluated on 10 cross-validation splits to determine the final ranking, whereas in 2017, only a single training-test split was used. While this greatly reduced the effort for the competition organizers, it increased the risk of a particular submission with randomized components getting lucky.

In general, our expectation for the performance of a submission is that it does not depend on randomness much, i.e., its performance does not vary significantly across different test sets or random seeds. On the other hand, as we observed in Section 5.3, achieving good performance across multiple scenarios is an issue.

To determine the effect of randomness on performance, we ran the competition winner, ASAP.v2, with different random seeds on the CSP-Minizinc-Obj-2016 (Camilla) scenario, where it performed particularly well. Fig. 6 shows the cumulative distribution function of the performance across different random seeds. The probability of ASAP.v2 performing as good or better than it did is very low, suggesting that it did choose a lucky random seed.

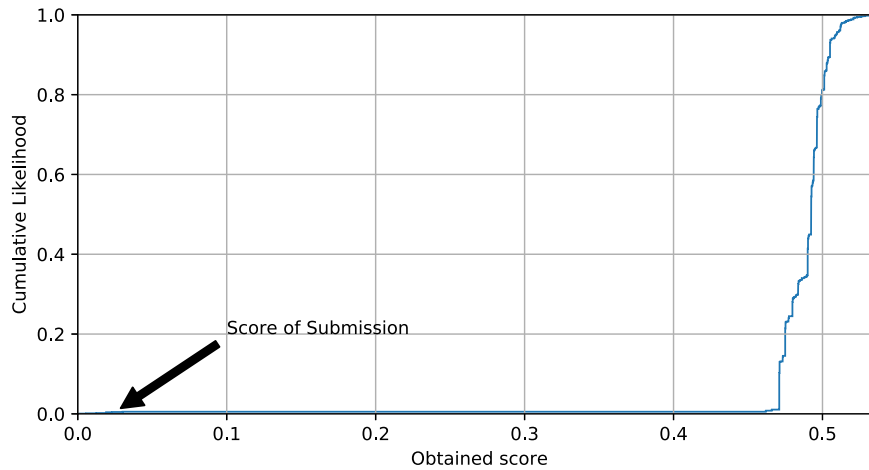


Fig. 6. Cumulative distribution function of the closed gap of ASAP.v2 on CSP-Minizinc-Obj-2016, across 1500 random seeds. The plot shows that the actual obtained score (0.025) has a probability of 0.466%.

This result demonstrates the importance of evaluating algorithm selection systems across multiple random seeds, or multiple test sets. If we replace ASAP's obtained score with the median score of the CDF shown in Fig. 6, it would have ranked at third place.

5.5. Hyperparameter optimization

All systems submitted to either of the competitions leverage a machine learning model that predicts the performance of algorithms. It is well known that hyperparameter optimization is important to get well-performing machine learning models (see, e.g., [49,51,55]). Nevertheless, not all submissions optimized hyperparameters, e.g., the winner in 2017 ASAP.v2 [17] used the default hyperparameters of its random forest. Given previous results by Lindauer et al. [38], we would expect that adding hyperparameter optimization to recent algorithm selection systems will further boost their performances.

5.6. Handling of quality scenarios

ASlib distinguishes between two types of scenarios: *runtime scenarios* and *quality scenarios*. In runtime scenarios, the goal is to minimize the time the selected algorithm requires to solve an instances (e.g., SAT, ASP), whereas in quality scenarios the goal is to find the algorithm that obtains the highest score or lowest error according to some metric (e.g., plan quality in AI planning or prediction error in Machine Learning). In the current version of ASlib, the most important difference between the two scenario types is that for runtime scenario a schedule of different algorithms can be provided, whereas for quality scenarios only a single algorithm. The reason for this limitation is that ASlib does not contain information on intermediate solution qualities of any-time algorithms (e.g., the solution quality after half the timeout). For the same reason, the cost of feature computation cannot be considered for quality scenarios – it is unknown how much additional quality could be achieved in the time required for feature computation. This setup is common in algorithm selection methods for machine learning (meta-learning). Intermediate solutions and the time at which they were obtained could enable schedules for quality scenarios and analyzing trade-offs between obtaining a better solution quality by expending more resources or switching to another algorithm. For example, the MiniZinc Challenge [50] started to record these information in 2017. Future versions of ASlib will consider addressing this limitation.

5.7. Challenging scenarios

On average, algorithm selection systems perform well and the best systems had a remaining gap between the single best and virtual best solver of only 38% in 2017. However, some of the scenarios are harder than others for algorithm selection. Table 5 shows the median and best performance of all submissions on all scenarios. To identify challenging scenarios, we studied the best-performing submission on each scenario and compared the remaining gap with the average remaining gap over all scenarios. In 2015, *SAT12-RAND* and *SAT11-INDU* were particularly challenging, and in 2017 *OPENML-WEKA-2017* and *SAT03-16-INDU*.

SAT12-RAND was a challenging scenario in 2015 and most of the participating systems performed not better than the single best solver on it, although the VBS has a 12-fold speedup over the single best solver. The main reason is probably that not only the SAT instances considered in this scenario are randomly generated but also most of the best-performing solvers are stochastic local search solvers which are highly randomized. The data in this

Table 5

Average remaining gap and the best remaining gap across all submissions for all scenarios. The **bold** scenarios are particularly challenging.

Scenario	Median rem. gap	Best rem. gap
2015		
ASP-POTASSCO	0.31	0.28
CSP-2010	0.23	0.14
MAXSAT12-PMS	0.18	0.14
CPMP-2013	0.35	0.29
PROTEUS-2014	0.16	0.05
QBF-2011	0.15	0.09
SAT11-HAND	0.34	0.30
SAT11-INDU	1.00	0.87
SAT11-RAND	0.08	0.04
SAT12-ALL	0.38	0.27
SAT12-HAND	0.32	0.25
SAT12-INDU	0.90	0.59
SAT12-RAND	1.00	0.77
Average	0.41	0.31
2017		
BNSL-2016	0.25	0.15
CSP-Minizinc-Obj-2016 ..	1.59	0.02
CSP-Minizinc-Time-2016 ..	0.41	0.05
MAXSAT-PMS-2016	0.49	0.41
MAXSAT-WPMS-2016	0.51	0.08
MIP-2016	0.56	0.49
OPENML-WEKA-2017	1.0	0.78
QBF-2016	0.43	0.15
SAT12-ALL	0.42	0.31
SAT03-16_INDU	0.77	0.65
TTP-2016*	0.33	0.15
Average	0.61	0.30

scenario was obtained from single runs of each algorithm, which introduces strong noise. After the competition in 2015, Cameron et al. [7] showed that in such noisy scenarios, the performance of the virtual best solver is often overestimated. Thus, we do not recommend to study algorithm selection on *SAT12-RAND* at this moment and plan to remove *SAT12-RAND* in the next ASlib release.

SAT11-INDU was a hard scenario in 2015; in particular it was hard for systems that selected schedules per instance (such as Sunny). Applying schedules on these industrial-like instances is quite hard because even the single best solver has an average PAR10 score of 8030 (with a timeout of 5000 seconds) to solve an instance; thus, allocating a fraction of the total available resources to an algorithm on this scenario is often not a good idea (also shown by Hoos et al. [20]).

SAT03-16_INDU was a challenging scenario for the participants in 2017. It is mainly an extension of a previously-used scenario called *SAT12-INDU*. Zilla was one of the best submissions in 2015 on *SAT12-INDU* with a remaining gap of roughly 61%; however in 2017 on *SAT03-16_INDU*, zilla had a remaining gap of 83%. Similar observations apply to ASAP. *SAT03-16_INDU* could be much harder than *SAT12-INDU* because of the smaller number of algorithms (31 \rightarrow 10), the larger number of instances (767 \rightarrow 2000) or the larger number of instance features (138 \rightarrow 483).

OPENML-WEKA-2017 was a new scenario in the 2017 competition and appeared to be very challenging, as six out of eight submissions performed almost equal to or worse than the single best solver ($\geq 95\%$ remaining gap). This scenario featured algorithm selection for machine learning problems (cf. meta-learning [5]). The objective was to select the best machine learning algorithm from a selection of WEKA algorithms [18], based on simple characteristics of the dataset (i.e., meta-features). The scenario was introduced by van Rijn [52] [Chapter 6]. We verified empirically that (i) there is a learnable concept in this scenario, and (ii) the chosen holdout set was sufficiently similar to the training data by evaluating a simple baseline algorithm selector (a regression approach using a random forest as model). The experimental setup and results are presented in Fig. 7. It is indeed a challenging scenario; on half of the sampled holdout sets, our baseline was unable to close the gap by more than 10%. In 18% of the holdout sets, the baseline performed worse than the SBS. However, our simple baseline achieved 67.5% remaining gap on the holdout set used in the competition (compared to the best submission Sunny-fkvar with 78%).

6. Conclusions

In this paper, we discussed the setup and results of two algorithm selection competitions. These competitions allow the community to objectively compare different systems and assess their benefits. They confirmed that per-instance algorithm

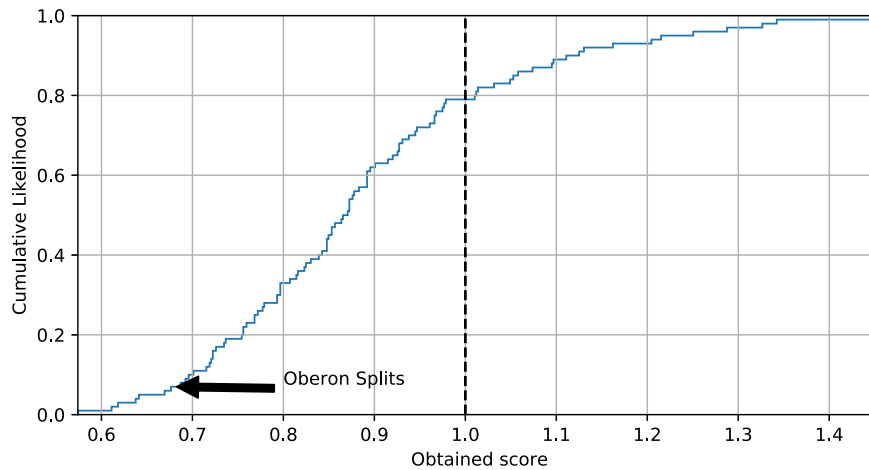


Fig. 7. Cumulative distribution function of the obtained gap-remaining score of a random forest regressor (a single model trained to predict for all classifiers, 64 trees) on 100 randomly sampled 33% holdout sets of the OPENML-WEKA-2017 scenario. The dashed line indicates the performance of the single best solver; the score on the actual splits as presented in Oberon was 0.675.

selection can substantially improve the state of the art in many areas of AI. For example, the virtual best solver obtains on average a 31.8 fold speedup over the single best solver on the runtime scenarios from 2017. While the submissions fell short of this perfect performance, they did achieve significant improvements.

Perhaps more importantly, the competitions highlighted challenges for the community in a field that has been well-established for more than a decade. We identified several challenging scenarios on which the recent algorithm selection systems do not perform well. Furthermore, there is no system that performs well on all types of scenarios – a meta-algorithm selection problem is very much relevant in practice and warrants further research. The competitions also highlighted restrictions in the current version of ASlib, which enabled the competitions, that need to be addressed in future work.

Acknowledgements

Marius Lindauer acknowledges funding by the DFG (German Research Foundation) under Emmy Noether grant HU 1900/2-1. Lars Kotthoff acknowledges funding from the National Science Foundation (NSF), award number 1813537.

Appendix A. Submitted systems in 2015

- ASAP based on random forests (RF) and k -nearest neighbor (kNN) as selection models combine pre-solving schedule and per-instance algorithm selection by training both jointly [16].
- *AutoFolio* combines several algorithm selection approaches in a single systems and uses algorithm configuration [26] to search for the best approach and its hyperparameter settings for the scenario at hand.
- *Sunny* selects an algorithm schedule on a per-instance base [1]. The time assigned to each algorithm is proportional to the number of solved instances in the neighborhood in the feature space with respect to the instance at hand.
- *Zilla* is the newest version of SATzilla [57,58] which uses pair-wise, cost-sensitive random forests combined with pre-solving schedules.
- *ZillaFolio* is a combination of Zilla and AutoFolio by evaluating both approaches on the training set and using the better approach for generating the predictions for the test set.

Appendix B. Technical evaluation details in 2015

The evaluation was performed as follows. For each scenario, 10 bootstrap samples of the entire data were used to create 10 different train/test splits. No stratification was used. The training part was left unmodified. For the test part, algorithm performances were set to 0 and runstatus to “ok” for all algorithms and all instances – the ASlib specification requires algorithm performance data to be part of a scenario.

There was a time limit of 12 hours for the training phase. Systems that exceeded this limit were disqualified. The time limit was chosen for practical reasons, to make it possible to evaluate the submissions with reasonable resource requirements.

For systems that specified a pre-solver, the instances that were solved by the pre-solver within the specified time were removed from the training set. If a subset of features was specified, only these features (and only the costs associated with these features) were left in both training and test set, with all other feature values removed.

Each system was trained on each train scenario and predicted on each test scenario. In total, 130 evaluations (10 for each of the 13 scenarios) per submitted system were performed. The total CPU time spent was 4685.11 hours on 8-core Xeon E5-2640 CPUs.

Each system was evaluated in terms of mean PAR10 score, mean misclassification penalty (the additional time that was required to solve an instance because an algorithm that was not the best was chosen; the difference to the VBS), and mean number of instances solved for each of the 130 evaluations on each scenario and split. These are the same performance measures used in ASlib, and enable a direct comparison.

The final score of a submission group (i.e. a system submitted for different ASlib scenarios) was computed as the average score over all ASlib scenarios. For scenarios for which no system belonging to the group was submitted, the performance of the single best algorithm was assumed.

Appendix C. Submitted systems in 2017

- Gonard et al. [17] submitted *ASAP.v2* and *ASAP.v3* [16]. ASAP combines pre-solving schedules and per-instance algorithm selection by training both jointly. The main difference between ASAP.v2 and ASAP.v3 is that ASAP.v2 used a pre-solving schedule with a fixed length of 3, whereas ASAP.v3 optimized the schedule length between 1 and 4 on a per-scenario base.
- Malone et al. [42] submitted *AS-RF* and *AS-ASL* [43]. It also combines pre-solving schedules and per-instance algorithm selection, whereas the selection model is a two-level stacking model with the first level being regression models to predict the performance of each algorithm and the second level combines these performance predictions in a multi-class model to obtain a selected algorithm. AS-RF uses random forest and AS-ASL used auto-sklearn [13] to obtain a machine learning model.
- Liu et al. [41] submitted *Sunny (autok and fkvar)* [1]. Sunny selects per-instance algorithm schedules with the goal of minimizing the number of possible timeouts. Sunny-autok optimized the neighborhood size on a per-scenario base [37] and Sunny.fkvar additionally also applied greedy forward selection for instance feature subset selection.
- Cameron et al. [8] submitted **Zilla (vanilla and dynamic)*, the successor of SATzilla [57,58]. *Zilla also combines per-solving schedules and pre-instance algorithm selection but based on pair-wise weighted random forest models. The dynamic version of *Zilla additionally uses the trained random forest to extract a per-instance algorithm schedule.⁶

Appendix D. Detailed results 2015 competition

See Tables D.6–D.8.

Table D.6

Original results of the PAR10 scores of the 2015 competition.

Scenario	Zilla	Zillafolio	Autofolio	Flexfolio-schedules
ASP-POTASSCO	537 (5.0)	516 (1.0)	525 (3.0)	527 (4.0)
CSP-2010	6582 (4.0)	6549 (2.0)	6621 (7.0)	6573 (3.0)
MAXSAT12-PMS	3524 (6.0)	3598 (8.0)	3559 (7.0)	3375 (1.0)
PREMARSHALLING-ASTAR-2013	2599 (5.0)	2722 (7.0)	2482 (4.0)	2054 (2.0)
PROTEUS-2014	5324 (7.0)	5070 (5.0)	5057 (4.0)	4435 (1.0)
QBF-2011	9339 (7.0)	9366 (8.0)	9177 (6.0)	8653 (1.0)
SAT11-HAND	17436 (3.0)	17130 (1.0)	17746 (6.0)	17560 (4.0)
SAT11-INDU	13418 (3.0)	13768 (4.0)	13314 (1.0)	14560 (6.0)
SAT11-RAND	9495 (2.0)	9731 (3.0)	9428 (1.0)	10339 (8.0)
SAT12-ALL	964 (1.0)	1100 (3.0)	1066 (2.0)	1436 (6.0)
SAT12-HAND	4370 (2.0)	4432 (4.0)	4303 (1.0)	4602 (6.0)
SAT12-INDU	2754 (3.0)	2680 (1.0)	2688 (2.0)	2972 (4.0)
SAT12-RAND	3139 (1.0)	3146 (2.0)	3160 (3.0)	3240 (7.0)
Average	6114 (3.8)	6139 (3.8)	6087 (3.6)	6179 (4.1)
Scenario	ASAP_RF	ASAP_kNN	Sunny	Sunny-presolv
ASP-POTASSCO	517 (2.0)	554 (7.0)	575 (8.0)	547 (6.0)
CSP-2010	6516 (1.0)	6601 (5.0)	6615 (6.0)	6704 (8.0)
MAXSAT12-PMS	3421 (3.0)	3395 (2.0)	3465 (4.0)	3521 (5.0)
PREMARSHALLING-ASTAR-2013	2660 (6.0)	2830 (8.0)	2151 (3.0)	1979 (1.0)
PROTEUS-2014	5169 (6.0)	5338 (8.0)	4866 (3.0)	4798 (2.0)
QBF-2011	8793 (2.0)	8813 (3.0)	8907 (4.0)	9044 (5.0)
SAT11-HAND	17581 (5.0)	17289 (2.0)	19130 (7.0)	19238 (8.0)
SAT11-INDU	13858 (5.0)	13359 (2.0)	14681 (7.0)	15160 (8.0)
SAT11-RAND	10018 (6.0)	9795 (4.0)	10212 (7.0)	9973 (5.0)
SAT12-ALL	1201 (5.0)	1181 (4.0)	1579 (7.0)	1661 (8.0)
SAT12-HAND	4434 (5.0)	4395 (3.0)	4823 (7.0)	4875 (8.0)
SAT12-INDU	3005 (6.0)	2974 (5.0)	3201 (8.0)	3173 (7.0)
SAT12-RAND	3211 (4.0)	3239 (6.0)	3263 (8.0)	3222 (5.0)
Average	6183 (4.3)	6136 (4.5)	6421 (6.1)	6453 (5.8)

⁶ *Zilla had a critical bug and the results were strongly degraded because of it. The authors of *Zilla submitted fixed results after the official deadline but before the test data and the results were announced. We list the fixed results of *Zilla; but these are not officially part of the competition.

Table D.7

Original results of the misclassification penalty scores of the 2015 competition.

Scenario	Zilla	Zillafolio	Autofolio	Flexfolio-schedules
ASP-POTASSCO	22 (5.0)	21 (2.0)	22 (3.0)	24 (7.0)
CSP-2010	14 (2.0)	11 (1.0)	28 (7.0)	23 (6.0)
MAXSAT12-PMS	38 (2.0)	42 (4.0)	177 (8.0)	41 (3.0)
PREMARSHALLING-ASTAR-2013	323 (5.0)	336 (7.0)	330 (6.0)	307 (4.0)
PROTEUS-2014	482 (8.0)	470 (7.0)	470 (6.0)	70 (1.0)
QBF-2011	192 (6.0)	194 (8.0)	182 (5.0)	133 (3.0)
SAT11-HAND	462 (3.0)	406 (1.0)	486 (5.0)	514 (6.0)
SAT11-INDU	615 (2.0)	639 (3.0)	574 (1.0)	779 (8.0)
SAT11-RAND	70 (3.0)	65 (2.0)	62 (1.0)	448 (8.0)
SAT12-ALL	95 (1.0)	111 (3.0)	103 (2.0)	211 (8.0)
SAT12-HAND	75 (1.0)	82 (3.0)	77 (2.0)	160 (8.0)
SAT12-INDU	87 (1.0)	100 (2.0)	103 (3.0)	139 (5.0)
SAT12-RAND	39 (1.0)	40 (2.0)	49 (4.0)	58 (5.0)
Average	194 (3.1)	194 (3.5)	205 (4.1)	224 (5.5)
Scenario	ASAP_RF	ASAP_kNN	Sunny	Sunny-presolv
ASP-POTASSCO	23 (6.0)	25 (8.0)	20 (1.0)	22 (4.0)
CSP-2010	14 (3.0)	21 (4.0)	22 (5.0)	39 (8.0)
MAXSAT12-PMS	45 (6.0)	43 (5.0)	31 (1.0)	57 (7.0)
PREMARSHALLING-ASTAR-2013	271 (1.0)	275 (2.0)	338 (8.0)	296 (3.0)
PROTEUS-2014	235 (4.0)	249 (5.0)	224 (3.0)	136 (2.0)
QBF-2011	98 (2.0)	80 (1.0)	181 (4.0)	194 (7.0)
SAT11-HAND	466 (4.0)	431 (2.0)	634 (8.0)	618 (7.0)
SAT11-INDU	736 (6.0)	673 (4.0)	701 (5.0)	772 (7.0)
SAT11-RAND	124 (6.0)	129 (7.0)	122 (5.0)	85 (4.0)
SAT12-ALL	157 (5.0)	153 (4.0)	182 (6.0)	183 (7.0)
SAT12-HAND	114 (5.0)	102 (4.0)	124 (6.0)	129 (7.0)
SAT12-INDU	160 (8.0)	154 (7.0)	154 (6.0)	138 (4.0)
SAT12-RAND	60 (7.0)	67 (8.0)	58 (6.0)	45 (3.0)
Average	193 (4.8)	185 (4.7)	215 (4.9)	209 (5.4)

Table D.8

Original results of the solved scores of the 2015 competition.

Scenario	Zilla	Zillafolio	Autofolio	Flexfolio-schedules
ASP-POTASSCO	0.915 (5.0)	0.919 (2.0)	0.917 (4.0)	0.918 (3.0)
CSP-2010	0.870 (4.0)	0.871 (2.0)	0.870 (6.0)	0.870 (3.0)
MAXSAT12-PMS	0.834 (7.0)	0.830 (8.0)	0.840 (4.0)	0.842 (1.0)
PREMARSHALLING-ASTAR-2013	0.937 (5.0)	0.933 (6.0)	0.940 (4.0)	0.953 (2.0)
PROTEUS-2014	0.863 (6.0)	0.871 (3.0)	0.871 (2.0)	0.878 (1.0)
QBF-2011	0.745 (7.0)	0.744 (8.0)	0.750 (6.0)	0.765 (1.0)
SAT11-HAND	0.659 (3.0)	0.665 (1.0)	0.653 (6.0)	0.658 (4.0)
SAT11-INDU	0.741 (3.0)	0.734 (5.0)	0.742 (2.0)	0.719 (6.0)
SAT11-RAND	0.815 (2.0)	0.809 (3.0)	0.816 (1.0)	0.804 (6.0)
SAT12-ALL	0.930 (1.0)	0.918 (3.0)	0.921 (2.0)	0.897 (6.0)
SAT12-HAND	0.643 (3.0)	0.638 (5.0)	0.649 (1.0)	0.629 (6.0)
SAT12-INDU	0.779 (3.0)	0.787 (1.0)	0.787 (2.0)	0.764 (5.0)
SAT12-RAND	0.742 (1.0)	0.742 (2.0)	0.741 (3.0)	0.735 (7.0)
Average	0.806 (3.8)	0.805 (3.8)	0.807 (3.3)	0.802 (3.9)
Scenario	ASAP_RF	ASAP_kNN	Sunny	Sunny-presolv
ASP-POTASSCO	0.919 (1.0)	0.913 (7.0)	0.908 (8.0)	0.913 (6.0)
CSP-2010	0.872 (1.0)	0.870 (5.0)	0.870 (7.0)	0.868 (8.0)
MAXSAT12-PMS	0.840 (3.0)	0.841 (2.0)	0.837 (5.0)	0.835 (6.0)
PREMARSHALLING-ASTAR-2013	0.933 (7.0)	0.928 (8.0)	0.951 (3.0)	0.955 (1.0)
PROTEUS-2014	0.861 (7.0)	0.856 (8.0)	0.870 (4.0)	0.869 (5.0)
QBF-2011	0.759 (2.0)	0.758 (4.0)	0.758 (3.0)	0.754 (5.0)
SAT11-HAND	0.656 (5.0)	0.662 (2.0)	0.625 (7.0)	0.623 (8.0)
SAT11-INDU	0.734 (4.0)	0.744 (1.0)	0.715 (7.0)	0.706 (8.0)
SAT11-RAND	0.804 (7.0)	0.809 (4.0)	0.800 (8.0)	0.804 (5.0)
SAT12-ALL	0.913 (5.0)	0.915 (4.0)	0.881 (7.0)	0.873 (8.0)
SAT12-HAND	0.640 (4.0)	0.643 (2.0)	0.605 (7.0)	0.601 (8.0)
SAT12-INDU	0.763 (6.0)	0.765 (4.0)	0.744 (8.0)	0.745 (7.0)
SAT12-RAND	0.738 (4.0)	0.736 (5.0)	0.733 (8.0)	0.735 (6.0)
Average	0.802 (4.3)	0.803 (4.3)	0.792 (6.3)	0.791 (6.2)

Appendix E. Detailed results 2017 competition

Table E.9

Original results of the 2017 competition – score of 0 refers to the virtual best solver and 1 to the single best solver.

Scenario	ASAP.v2	ASAP.v3	Sunny-fkvar	Sunny-autok
Bado	0.239 (4.0)	0.192 (3.0)	0.153 (1.0)	0.252 (5.0)
Camilla	0.025 (1.5)	0.025 (1.5)	0.894 (3.0)	1.475 (4.0)
Caren	0.412 (5.0)	0.410 (4.0)	0.055 (1.0)	0.217 (2.0)
Magnus	0.492 (4.0)	0.494 (5.0)	0.419 (3.0)	0.498 (6.0)
Mira	0.495 (2.0)	0.491 (1.0)	0.568 (4.0)	1.014 (6.0)
Monty	0.167 (2.0)	0.237 (3.0)	0.090 (1.0)	0.368 (4.0)
Oberon	0.950 (3.5)	0.950 (3.5)	0.787 (1.0)	0.877 (2.0)
Quill	0.302 (2.0)	0.420 (3.0)	0.431 (4.0)	0.150 (1.0)
Sora	0.650 (1.0)	0.775 (4.0)	0.821 (5.0)	0.827 (6.0)
Svea	0.324 (2.0)	0.312 (1.0)	0.342 (3.0)	0.421 (4.0)
Titus	0.154 (1.5)	0.154 (1.5)	0.201 (4.0)	0.195 (3.0)
Average	0.383 (2.6)	0.405 (2.8)	0.433 (2.7)	0.572 (3.9)
Scenario	Star-zilla_dyn_sched	Star-zilla	AS-RF	AS-ASL
Bado	0.516 (8.0)	0.293 (6.0)	0.164 (2.0)	0.319 (7.0)
Camilla	3.218 (7.5)	3.218 (7.5)	1.974 (5.0)	2.289 (6.0)
Caren	0.223 (3.0)	1.001 (6.0)	1.659 (7.0)	2.068 (8.0)
Magnus	0.410 (1.0)	0.417 (2.0)	2.012 (7.0)	2.013 (8.0)
Mira	2.337 (8.0)	0.967 (5.0)	0.505 (3.0)	1.407 (7.0)
Monty	0.513 (5.0)	0.827 (6.0)	8.482 (8.0)	7.973 (7.0)
Oberon	1.000 (5.5)	1.000 (5.5)	3.798 (7.0)	7.233 (8.0)
Quill	0.541 (5.0)	0.692 (6.0)	1.328 (8.0)	1.299 (7.0)
Sora	0.687 (2.5)	0.687 (2.5)	1.135 (7.0)	1.383 (8.0)
Svea	0.829 (7.5)	0.829 (7.5)	0.543 (5.0)	0.561 (6.0)
Titus	0.335 (5.5)	0.335 (5.5)	1.535 (8.0)	1.113 (7.0)
Average	0.964 (5.3)	0.933 (5.4)	2.103 (6.1)	2.514 (7.2)

References

- [1] R. Amadini, M. Gabbriellini, J. Mauro, SUNNY: a lazy portfolio approach for constraint solving, *Theory Pract. Log. Program.* 14 (4–5) (2014) 509–524.
- [2] C. Ansótegui, J. Gabàs, Y. Malitsky, M. Sellmann, Maxsat by improved instance-specific algorithm configuration, *Artif. Intell.* 235 (2016) 26–39.
- [3] C. Ansótegui, M. Sellmann, K. Tierney, A gender-based genetic algorithm for the automatic configuration of algorithms, in: I. Gent (Ed.), *Proceedings of the Fifteenth International Conference on Principles and Practice of Constraint Programming, CP'09*, in: *Lecture Notes in Computer Science*, vol. 5732, Springer-Verlag, 2009, pp. 142–157.
- [4] B. Bischl, P. Kerschke, L. Kotthoff, M. Lindauer, Y. Malitsky, A. Frechétte, H. Hoos, F. Hutter, K. Leyton-Brown, K. Tierney, J. Vanschoren, ASlib: a benchmark library for algorithm selection, *Artif. Intell.* (2016) 41–58.
- [5] P. Brazdil, C. Giraud-Carrier, C. Soares, R. Vilalta, *Metalearning: Applications to Data Mining*, 1st edition, Springer Publishing Company, 2008, Incorporated.
- [6] F. Calimeri, D. Fusca, S. Perri, J. Zangari, I-DLV+MS: preliminary report on an automatic asp solver selector, in: *Proceedings of the 24th RCRA International Workshop on Experimental Evaluation of Algorithms for Solving Problems with Combinatorial Explosion*, 2017, pp. 26–32.
- [7] C. Cameron, H. Hoos, K. Leyton-Brown, Bias in algorithm portfolio performance evaluation, in: S. Kambhampati (Ed.), *Proceedings of the Twenty-Fifth International Joint Conference on Artificial Intelligence, IJCAI, IJCAI/AAAI Press*, 2016, pp. 712–719.
- [8] C. Cameron, H.H. Hoos, K. Leyton-Brown, F. Hutter, Oasc-2017: *zilla submission, in: M. Lindauer, J.N. van Rijn, L. Kotthoff (Eds.), *Proceedings of the Open Algorithm Selection Challenge*, vol. 79, 2017, pp. 15–18.
- [9] J. Carpenter, May the best analyst win, *Science* 331 (6018) (2011) 698–699.
- [10] J. Demsar, Statistical comparisons of classifiers over multiple data sets, *J. Mach. Learn. Res.* 7 (2006) 1–30.
- [11] A. Dutt, J. Haritsa, Plan bouquets: a fragrant approach to robust query processing, *ACM Trans. Database Syst.* 41 (2) (2016) 1–37.
- [12] M. Feuer, K. Eggersperger, S. Falkner, M. Lindauer, F. Hutter, Practical automated machine learning for the AutoML challenge 2018, in: *ICML 2018 AutoML Workshop*, July 2018.
- [13] M. Feuer, A. Klein, K. Eggersperger, J.T. Springenberg, M. Blum, F. Hutter, Efficient and robust automated machine learning, in: C. Cortes, N. Lawrence, D. Lee, M. Sugiyama, R. Garnett (Eds.), *Proceedings of the 29th International Conference on Advances in Neural Information Processing Systems, NIPS'15*, 2015, pp. 2962–2970.
- [14] M. Feuer, T. Springenberg, F. Hutter, Initializing Bayesian hyperparameter optimization via meta-learning, in: B. Bonet, S. Koenig (Eds.), *Proceedings of the Twenty-Ninth National Conference on Artificial Intelligence, AAAI'15, AAAI Press*, 2015, pp. 1128–1135.
- [15] C. Gomes, B. Selman, Algorithm portfolios, *Artif. Intell.* 126 (1–2) (2001) 43–62.
- [16] F. Gonard, M. Schoenauer, M. Sebag, Algorithm selector and prescheduler in the icon challenge, in: *Proceedings of the International Conference on Metaheuristics and Nature Inspired Computing, META'2016*, 2016.
- [17] F. Gonard, M. Schoenauer, M. Sebag, Asap.v2 and asap.v3: sequential optimization of an algorithm selector and a scheduler, in: M. Lindauer, J.N. van Rijn, L. Kotthoff (Eds.), *Proceedings of the Open Algorithm Selection Challenge*, vol. 79, 2017, pp. 8–11.
- [18] M. Hall, E. Frank, G. Holmes, B. Pfahringer, P. Reutemann, I. Witten, The WEKA data mining software: an update, *ACM SIGKDD Explor. Newsl.* 11 (1) (2009) 10–18.
- [19] M. Helmert, G. Röger, E. Karpas, Fast downward stone soup: a baseline for building planner portfolios, in: *ICAPS-2011 Workshop on Planning and Learning, PAL*, 2011, pp. 28–35.
- [20] H. Hoos, R. Kaminski, M. Lindauer, T. Schaub, aspeed: solver scheduling via answer set programming, *Theory Pract. Log. Program.* 15 (2015) 117–142.
- [21] H. Hoos, M. Lindauer, T. Schaub, claspfolio 2: advances in algorithm selection for answer set programming, *Theory Pract. Log. Program.* 14 (2014) 569–585.

- [22] H. Hoos, T. Peitl, F. Slivovsky, S. Szeider, Portfolio-based algorithm selection for circuit qbfs, in: J.N. Hooker (Ed.), *Proceedings of the International Conference on Principles and Practice of Constraint Programming*, in: *Lecture Notes in Computer Science*, vol. 11008, Springer, 2018, pp. 195–209.
- [23] E. Horvitz, Y. Ruan, C. Gomes, H. Kautz, B. Selman, M. Chickering, A bayesian approach to tackling hard computational problems, in: *Proceedings of the Seventeenth Conference on Uncertainty in Artificial Intelligence*, Morgan Kaufmann Publishers Inc., 2001, pp. 235–244.
- [24] B. Huberman, R. Lukose, T. Hogg, An economic approach to hard computational problems, *Science* 275 (1997) 51–54.
- [25] B. Hurley, L. Kotthoff, Y. Malitsky, B. O'Sullivan, Proteus: a hierarchical portfolio of solvers and transformations, in: H. Simonis (Ed.), *Proceedings of the Eleventh International Conference on Integration of AI and OR Techniques in Constraint Programming*, CPAIOR'14, in: *Lecture Notes in Computer Science*, vol. 8451, Springer-Verlag, 2014, pp. 301–317.
- [26] F. Hutter, H. Hoos, K. Leyton-Brown, Sequential model-based optimization for general algorithm configuration, in: C. Coello (Ed.), *Proceedings of the Fifth International Conference on Learning and Intelligent Optimization*, LION'11, in: *Lecture Notes in Computer Science*, vol. 6683, Springer-Verlag, 2011, pp. 507–523.
- [27] F. Hutter, L. Xu, H. Hoos, K. Leyton-Brown, Algorithm runtime prediction: methods and evaluation, *Artif. Intell.* 206 (2014) 79–111.
- [28] S. Kadioglu, Y. Malitsky, A. Sabharwal, H. Samulowitz, M. Sellmann, Algorithm selection and scheduling, in: J. Lee (Ed.), *Proceedings of the Seventeenth International Conference on Principles and Practice of Constraint Programming*, CP'11, in: *Lecture Notes in Computer Science*, vol. 6876, Springer-Verlag, 2011, pp. 454–469.
- [29] M. Katz, S. Sohrabi, H. Samulowitz, S. Sievers, Delfi: online planner selection for cost-optimal planning, in: *Ninth International Planning Competition*, IPC 2018, 2018, pp. 55–62.
- [30] R. Koitz, F. Wotawa, Improving abductive diagnosis through structural features: a meta-approach, in: *Proceedings of the International Workshop on Defeasible and Ampliative Reasoning (DARE-16)*, CEUR WS Proceedings, 2016.
- [31] L. Kotthoff, Hybrid regression-classification models for algorithm selection, in: *20th European Conference on Artificial Intelligence*, Aug. 2012, pp. 480–485.
- [32] L. Kotthoff, LLAMA: leveraging learning to automatically manage algorithms, arXiv:1306.1031, 2013.
- [33] L. Kotthoff, Algorithm selection for combinatorial search problems: a survey, *AI Mag.* 35 (3) (2014) 48–60.
- [34] L. Kotthoff, ICON challenge on algorithm selection, CoRR 2015, arXiv:1511.04326, <http://arxiv.org/abs/1511.04326>.
- [35] L. Kotthoff, B. Hurley, B. O'Sullivan, The ICON challenge on algorithm selection, *AI Mag.* 38 (2) (2017) 91–93.
- [36] L. Kotthoff, P. Kerschke, H. Hoos, H. Trautmann, Improving the state of the art in inexact TSP solving using per-instance algorithm selection, in: C. Dhaenens, L. Jourdan, M. Marmion (Eds.), *Proceedings of the Ninth International Conference on Learning and Intelligent Optimization*, LION'15, in: *Lecture Notes in Computer Science*, Springer-Verlag, 2015, pp. 202–217.
- [37] M. Lindauer, D. Bergdoll, F. Hutter, An empirical study of per-instance algorithm scheduling, in: P. Festa, M. Sellmann, J. Vanschoren (Eds.), *Proceedings of the Tenth International Conference on Learning and Intelligent Optimization*, LION'16, in: *Lecture Notes in Computer Science*, Springer-Verlag, 2016, pp. 253–259.
- [38] M. Lindauer, H. Hoos, F. Hutter, T. Schaub, Autofolio: an automatically configured algorithm selector, *J. Artif. Intell. Res.* 53 (Aug. 2015) 745–778.
- [39] M. Lindauer, H. Hoos, K. Leyton-Brown, T. Schaub, Automatic construction of parallel portfolios via algorithm configuration, *Artif. Intell.* 244 (2017) 272–290.
- [40] M. Lindauer, J.N. van Rijn, L. Kotthoff, Open algorithm selection challenge 2017: setup and scenarios, in: M. Lindauer, J.N. van Rijn, L. Kotthoff (Eds.), *Proceedings of the Open Algorithm Selection Challenge*, vol. 79, 2017, pp. 1–7.
- [41] T. Liu, R. Amadini, J. Mauro, Sunny with algorithm configuration, in: M. Lindauer, J.N. van Rijn, L. Kotthoff (Eds.), *Proceedings of the Open Algorithm Selection Challenge*, vol. 79, 2017, pp. 12–14.
- [42] B. Malone, K. Kangas, M. Järvisalo, M. Koivisto, P. Myllymäki, as-asl: algorithm selection with auto-sklearn, in: M. Lindauer, J.N. van Rijn, L. Kotthoff (Eds.), *Proceedings of the Open Algorithm Selection Challenge*, vol. 79, 2017, pp. 19–22.
- [43] B. Malone, K. Kangas, M. Järvisalo, M. Koivisto, P. Myllymäki, Empirical hardness of finding optimal bayesian network structures: algorithm selection and runtime prediction, *Mach. Learn.* (2018) 247–283.
- [44] M. Maratea, L. Pulina, F. Ricca, A multi-engine approach to answer-set programming, *Theory Pract. Log. Program.* 14 (6) (2015) 841–868.
- [45] J. Rice, The algorithm selection problem, *Adv. Comput.* 15 (1976) 65–118.
- [46] H. Samulowitz, C. Reddy, A. Sabharwal, M. Sellmann, Snappy: a simple algorithm portfolio, in: M. Järvisalo, A.V. Gelder (Eds.), *Proceedings of the 16th International Conference on Theory and Applications of Satisfiability Testing*, in: *Lecture Notes in Computer Science*, vol. 7962, Springer, 2013, pp. 422–428.
- [47] P. Selvaraj, V. Nagarajan, PCE-based path computation algorithm selection framework for the next generation SDON, *J. Theor. Appl. Inf. Technol.* 95 (11) (2017) 2370–2382.
- [48] K. Smith-Miles, Cross-disciplinary perspectives on meta-learning for algorithm selection, *ACM Comput. Surv.* 41 (1) (2008).
- [49] J. Snoek, H. Larochelle, R.P. Adams, Practical Bayesian optimization of machine learning algorithms, in: P. Bartlett, F. Pereira, C. Burges, L. Bottou, K. Weinberger (Eds.), *Proceedings of the 26th International Conference on Advances in Neural Information Processing Systems*, NIPS'12, 2012, pp. 2960–2968.
- [50] P. Stuckey, T. Feydy, A. Schutt, G. Tack, J. Fischer, The minizinc challenge 2008–2013, *AI Mag.* 35 (2) (2014) 55–60.
- [51] C. Thornton, F. Hutter, H. Hoos, K. Leyton-Brown, Auto-WEKA: combined selection and hyperparameter optimization of classification algorithms, in: I. Dhillon, Y. Koren, R. Ghani, T. Senator, P. Bradley, R. Parekh, J. He, R. Grossman, R. Uthurusamy (Eds.), *The 19th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, KDD'13, ACM Press, 2013, pp. 847–855.
- [52] J.N. van Rijn, *Massively Collaborative Machine Learning*, Ph.D. thesis, Leiden University, 2016.
- [53] J.N. van Rijn, S. Abdulrahman, P. Brazdil, J. Vanschoren, Fast algorithm selection using learning curves, in: *Advances in Intelligent Data Analysis XIV*, Springer, 2015, pp. 298–309.
- [54] J.N. van Rijn, G. Holmes, B. Pfahringer, J. Vanschoren, The online performance estimation framework: heterogeneous ensemble learning for data streams, *Mach. Learn.* 107 (1) (2018) 149–167.
- [55] J.N. van Rijn, F. Hutter, Hyperparameter importance across datasets, in: *Proceedings of the 24th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, ACM, 2018, pp. 2367–2376.
- [56] J. Vanschoren, J.N. van Rijn, B. Bischl, L. Torgo, OpenML: networked science in machine learning, *ACM SIGKDD Explor. Newsl.* 15 (2) (2014) 49–60.
- [57] L. Xu, F. Hutter, H. Hoos, K. Leyton-Brown, SATzilla: portfolio-based algorithm selection for SAT, *J. Artif. Intell. Res.* 32 (2008) 565–606.
- [58] L. Xu, F. Hutter, H. Hoos, K. Leyton-Brown, Hydra-MIP: automated algorithm configuration and selection for mixed integer programming, in: *RCRA Workshop on Experimental Evaluation of Algorithms for Solving Problems with Combinatorial Explosion at the International Joint Conference on Artificial Intelligence*, IJCAI, 2011.
- [59] L. Xu, F. Hutter, H. Hoos, K. Leyton-Brown, Evaluating component solver contributions to portfolio-based algorithm selectors, in: A. Cimatti, R. Sebastiani (Eds.), *Proceedings of the Fifteenth International Conference on Theory and Applications of Satisfiability Testing*, SAT'12, in: *Lecture Notes in Computer Science*, vol. 7317, Springer-Verlag, 2012, pp. 228–241.