

# Explainable Planner Selection for Classical Planning

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## Abstract

Since no classical planner consistently outperforms all others, it is important to select a planner that works well for a given classical planning task. The two strongest approaches for planner selection use image and graph convolutional neural networks. They have the drawback that the learned models are complicated and uninterpretable. To obtain explainable models, we identify a small set of simple task features and show that elementary and interpretable machine learning techniques can use these features to solve roughly as many tasks as the complex approaches based on neural networks.

## Introduction

Classical planning is the task of finding a sequence of actions that transforms an initial state into a goal state (Ghalab, Nau, and Traverso 2004). Over the last decades researchers introduced a large collection of planning algorithms, also called *planners*. All of them exhibit different strengths and weaknesses and therefore no single planner is preferable to all others for all planning tasks (e.g., Howe et al. 1999; Seipp et al. 2012). Consequently, it is often beneficial to combine multiple planners in a *portfolio*.

There are several types of portfolios, differing in whether they run a single or multiple planners and whether the planners, their time limits and their order are chosen offline, before seeing the task or online, when the task is known. For an overview of planning portfolios, see Vallati (2012) and Cenamor, de la Rosa, and Fernández (2016).

The first category of portfolio approaches from the literature learns a schedule for multiple planners offline (e.g., Helmert, Röger, and Karpas 2011; Núñez, Borrajo, and Linares López 2015; Seipp et al. 2015). The schedule defines the order and time limits for a set of planners which are then run in sequence. This approach is based on the insight that a planner often solves a task either quickly or not at all within the given resource limits.

The second category of planning portfolios computes a schedule of multiple planners online for a given input task (e.g., Roberts and Howe 2006). In the setting of satisficing planning, Cenamor, de la Rosa, and Fernández (2016) let their IBaCoP system predict a useful subset of planners, and

for optimal planning Ma et al. (2020) predict which planner has the highest chance of solving a task and which second planner is most likely to solve it if the first planner fails.

In this work, we focus on the simplest type of online planner scheduling: portfolio-based planner selection (Xu et al. 2008). Planner selectors have a collection of planners and predict the runtime of each planner or the likelihood of each planner solving the given task. Based on these predictions, they select and execute a single planner.

We want to analyze how complex performance models for planners have to be, in order for them to compete with the strongest planner selectors. Focusing on portfolio selection simplifies this analysis, because a single planner selection is easier to analyze than a selected subset of planners and their runtimes. Also, running a single planner often incurs shorter runtimes and is sometimes necessary to solve hard tasks. Finally, the IBaCoP system (Cenamor, de la Rosa, and Fernández 2016) already demonstrates for the subset-selection case that it is possible to learn strong models that are interpretable at the same time.

When building a planner selector, an important step is finding a set of suitable features to describe the task for the predicting model. Fawcett et al. (2014) collect a large set of handcrafted features and train different models for predicting the runtimes of several planners. In the same spirit, de la Rosa, Cenamor, and Fernández (2017) design features that help to discriminate between planner runtimes for planning instances that differ only in the random seed passed to the instance generator.

To avoid handcrafting features and potentially ignoring important features Sievers et al. (2019a) translate a given task into a graph (Sievers et al. 2019b) which preserves all information about the original task. They interpret the adjacency matrix of the graph as an image, scale the image down to 128x128 pixels, and train a convolutional neural network (CNN) to predict which planner will solve the given task. The hope is that the neural network automatically detects good features and indeed their model results in a strong planner which won in the International Planning Competition (IPC) in 2018. This is quite surprising since the 128x128 pixel image ignores a lot of information: many entries of the adjacency matrix are combined into the same pixel and the image does not distinguish between different types of nodes in the original graph. Nonetheless, the coverage scores of

the resulting portfolio selector suggests that the remaining information in the image is sufficient for planner selection. In a follow-up paper, Ma et al. (2020) eliminate the lossy transformation from graphs to images by directly feeding the graphs into graph convolutional networks (GCN; Kipf and Welling 2017). This causes a modest performance improvement and implies that the images already contain enough information for good predictions.

The drawback of the neural network approaches is that the learned models are not interpretable, that is, we cannot ask a model *why* it selects a certain planner and *which task features* are actually important for the selection (Cybenko 1989; Rudin 2019). Only models that can answer these questions can be deployed with confidence and will help us to understand the relative strengths of the component planners.

In this work, we show that complex black-box models such as (graph) convolutional neural networks are not needed to learn strong planner selectors. Indeed, we train the most elementary machine learning techniques with understandable task features and obtain portfolios selectors for optimal planning that solve approximately as many tasks as the complex approaches based on neural networks. In addition, our models have the advantage that they are explainable and fast to train. Furthermore, we analyze which features are important and which features can be ignored for accurate predictions. We examine which planners our models choose and whether they know when to choose them. Additionally, we show how to visualize and understand the choices of a simple planner selection model.

## Background

We train machine learning models that select a suitable planner for a given PDDL planning task (McDermott et al. 1998). Informally, a PDDL task defines a set of objects, a set of first-order predicates, and a set of action schemas. The objects are used when grounding the predicates and action schemas. The task uses the grounded predicates to describe an initial state and a goal condition. The grounded actions determine how a state can be transformed into a new state. A planner tries to find a sequence of actions that transforms the initial state into a state which satisfies the goal condition.

The machine learning techniques we use, in decreasing order of interpretability, are linear regression, decision trees, random forests, and multi-layer perceptrons. Each model takes as input a vector  $\vec{v} \in \mathbb{R}^N$  containing the values of the input features.

Linear regression (Galton 1886) learns a real-valued weight for each feature. The output of a linear regression model is the sum over the weighted features. Since linear regression chooses the weights to minimize the squared error, the learned models often use irrelevant features which in turn causes overfitting. Thus, we also use linear regression with L1 regularization (Tibshirani 1996). L1 regularization (in contrast to L2 regularization) incentivizes setting the weights of unnecessary features to 0, yielding simpler models.

A decision tree (Breiman et al. 1984) is a classifier which asks a sequence of questions and then predicts a single class. To train a decision tree, we start with a single root node and

assign all training examples to this node. Then, the training algorithm selects a feature and a threshold to split the training data such that some impurity metric (e.g., *Gini score*) is optimized. The feature and threshold are stored for the current node and the two parts of the split training data are associated with the two children of the current node. The algorithm is recursively applied to the children nodes until all samples associated to a node belong to the same class or some stopping criterion is reached.

Random forests (Breiman 2001) are an ensemble of decision trees. Here, we optimize multiple decision trees independently and obtain the overall prediction by averaging over the individual predictions.

For completeness, we also train multi-layer perceptrons (MLP; Goodfellow, Bengio, and Courville 2016). They are the simplest kind of neural network, much simpler than (graph) convolution networks. Still, they are not easily interpretable anymore. An MLP consists of multiple layers of neurons. Each layer is densely connected to the next layer. The value for each neuron is the weighted sum of the neurons connected to it (cf. linear regression). The value of the neuron is modified by a non-linear function (e.g.,  $ReLU(x) = \max(0, x)$ ) and is forwarded to the next neurons. The output of an MLP are the values of the neurons in the final layer.

## Training

For each task in our benchmark set, we compute the values of our features and measure the runtimes of a set of planners for the task. Then we use supervised learning to train models for planner selection. To be comparable to previous work, we use the data set from Ferber et al. (2019), which contains both a list of benchmark tasks and their planner runtimes.

**Benchmarks** The benchmarks in the data set stem from the 1998–2018 classical planning tracks of the IPC. Additionally, the set includes the domains BRIEFCASEWORLD, FERRY, and HANOI from the IPP benchmark collection (Köhler 1999), the GEDP domain (Haslum 2011), domains from the T0 conformant-to-classical planning compilation (Palacios and Geffner 2009), and the FSC domain (Bonet, Palacios, and Geffner 2009). All runtime measurements are limited to 30 minutes and 7744 MiB of memory. We keep only those tasks from the data set that at least one of the planners below solves within these limits. This leaves us with 2439 tasks, 145 of which were introduced for the IPC 2018.

**Features** For each task in the data set we compute four different sets of features. The first set (FAWCETT) is the one used by Fawcett et al. (2014). It contains features from the PDDL description of the task (e.g., the number of action schemas), features from its translation to a SAS<sup>+</sup> task (e.g., the number of mutex groups) and to a SAT formula, features from short runs with Fast Downward, and many more. These features are interpretable for domain experts, but some take very long to compute or require additional expertise to understand them. To analyze how complex features have to be for good planner selection, the second feature set (FPDDL) uses only the PDDL features of Fawcett et al. (2014). These

		Linear Regression					MLP		Rnd. Forest
		0.0	0.1	1.0	2.0	5.0	3	5	50
FAWCETT	binary	78.6 (8.3)	77.2 (10.5)	82.1 (8.7)	82.4 (9.4)	80.9 (9.4)	<b>87.1 (6.1)</b>	78.2 (15.3)	<b>84.8 (7.5)</b>
	logtime	79.3 (9.2)	79.0 (10.0)	81.5 (7.7)	81.7 (6.5)	83.6 (5.2)	82.2 (8.4)	82.2 (8.4)	84.1 (7.1)
	time	78.6 (8.2)	81.8 (7.1)	80.5 (7.5)	80.4 (7.2)	80.3 (7.9)	82.2 (7.6)	<b>85.3 (6.7)</b>	81.8 (15.7)
FPDDL	binary	<b>87.7 (7.2)</b>	74.3 (15.1)	72.7 (15.7)	74.3 (16.6)	71.4 (15.4)	81.0 (8.0)	81.5 (7.3)	77.5 (16.0)
	logtime	82.5 (11.8)	84.0 (6.8)	78.5 (8.3)	77.7 (9.0)	80.3 (8.4)	78.2 (6.2)	79.7 (7.6)	82.0 (6.1)
	time	86.5 (7.8)	<b>86.5 (7.8)</b>	<b>86.5 (7.9)</b>	<b>86.6 (7.8)</b>	<b>86.6 (7.8)</b>	80.2 (6.6)	81.9 (6.0)	78.8 (15.5)
PDDL	binary	81.4 (9.3)	75.7 (12.1)	72.6 (16.3)	74.1 (16.6)	71.4 (15.4)	78.1 (9.9)	79.8 (6.8)	80.2 (13.3)
	logtime	82.1 (8.4)	79.7 (11.2)	80.4 (9.1)	79.8 (8.7)	77.8 (13.0)	79.5 (8.2)	78.0 (7.5)	82.8 (7.0)
	time	81.6 (8.9)	82.0 (9.1)	81.2 (10.1)	79.0 (10.9)	78.7 (11.6)	77.8 (11.0)	78.4 (10.0)	79.7 (16.7)
UNION	binary	74.8 (9.7)	81.0 (8.3)	79.4 (11.1)	82.4 (9.3)	80.9 (9.4)	84.7 (7.7)	78.3 (13.6)	82.1 (8.5)
	logtime	75.6 (10.2)	80.0 (9.2)	80.7 (7.9)	81.8 (6.7)	83.4 (5.8)	82.2 (8.4)	82.2 (8.4)	84.7 (7.6)
	time	74.8 (8.8)	77.3 (11.9)	75.7 (11.0)	76.1 (11.5)	77.1 (10.3)	84.3 (6.8)	83.6 (7.7)	84.0 (13.9)
average		80.3	79.9	79.3	79.7	79.4	81.5	80.8	81.9

Table 1: Mean coverage and in brackets standard deviation (in %) over ten domain-preserving test folds for linear regression models with different L1 regularization weights, MLPs with 3 and 5 layers, and a random forest with 50 trees trained on (FAWCETT) the features of Fawcett et al. (2014), (FPDDL) the PDDL features of Fawcett et al. (2014), (PDDL) the extended set of PDDL features, and (UNION) the union of all features. The best setting in each column is highlighted.

features are very easy to interpret and they only require access to the PDDL files (i.e., no grounding, external planner or SAT solver is needed). The third feature set (PDDL) extends the FPDDL set with further PDDL features such as the minimum, mean, and maximum number of prevail conditions in all actions or the ratio of initial state facts over the number of objects. The fourth and last set (UNION) is the union of the other three feature sets.

**Planners** We use the same 17 optimal planners as Sievers et al. (2019a) and Ma et al. (2020): SymBA\* (Torralba et al. 2017) and 16 Fast Downward configurations (Helmert 2006). All Fast Downward configurations use A\* search (Hart, Nilsson, and Raphael 1968) and strong stubborn sets (Wehrle and Helmert 2014). Each of the following eight heuristics is used twice, once with DKS structural symmetries pruning (Domshlak, Katz, and Shleyfman 2012; Shleyfman et al. 2015) and once with structural symmetries pruning using orbital space search (OSS; Domshlak, Katz, and Shleyfman 2015): blind heuristic, LM-Cut (Helmert and Domshlak 2009), iPDB (Haslum et al. 2007), a zero-one cost partitioning pattern database (ZO-PDB) using a genetic algorithm to compute the patterns (Edelkamp 2006), and four Merge-and-shrink (M&S) heuristics (Dräger, Finkbeiner, and Podelski 2006; Helmert et al. 2014) using bisimulation (BS) (Nissim, Hoffmann, and Helmert 2011), full pruning (Sievers 2017),  $\Theta$ -combinability (Sievers, Wehrle, and Helmert 2014), partial abstractions (Sievers 2018), and merging based on either DFP (Sievers, Wehrle, and Helmert 2014), strongly connected components (SCC) of the causal graph (Sievers, Wehrle, and Helmert 2016), MIASM (Fan, Müller, and Holte 2014), or score-based MIASM (sbMI-ASM; Sievers, Wehrle, and Helmert 2016). All planners except for two M&S configurations use  $h^2$  mutexes to prune

irrelevant actions (Alcázar and Torralba 2015).

**Target Functions** We compare three different target functions for the machine learning models: *time*, *logtime* and *binary*. The first variant (*time*) predicts for each planner the time expected for the planner to solve the task. Then we can select the planner with the shortest expected runtime. Because the runtime distribution is heavily skewed to short runtimes, we also train models on the logarithmically-scaled runtimes, called *logtime*. In the end, we are not interested in selecting the fastest planner for a task, but the planner with the highest chance to solve the task. Therefore, we also train our models on the *binary* information whether a planner solves a task within the resource limits.

**Machine Learning Models** We use three types of machine learning techniques. First, we train plain linear regression models (Galton 1886) and linear regression models with L1 regularization (Tibshirani 1996) using regularization weights of 0.1, 1.0, 2.0 and 5.0. Second, we train random forests (Breiman 2001), i.e., ensembles of decision trees (Breiman et al. 1984). Linear regression and random forests internally train an independent model for each planner. Finally, we train fully-connected multi-layer perceptrons (MLP) with 3 and 5 layers. Although they are one of the simplest kind of neural networks, they are not easily explainable. We include them mainly as an intermediate approach between Delfi, which uses a complex neural network with learned latent features, and linear regression, which can be seen as a single-layer network with handcrafted features. The last layer of our MLP models contains an output neuron for every planner. We use the Adam optimizer (Kingma and Ba 2015) with a learning rate of 0.001 to optimize the weights. For the networks that predict the *time* or *logtime* we use the *ReLU* activation function and the *mean squared*

Feature	Decline	Feature	Decline
req. neg. pre.	4.4 (10.0)	#goals	1.2 (7.6)
max params per pred.	2.7 (7.0)	has types	1.0 (7.9)
mean neg. per eff	2.6 (10.6)	min pred. per pre.	0.9 (8.2)
mean pred. per eff	2.4 (10.2)	#predicates	0.9 (7.2)
req. cond. eff.	2.1 (9.1)	req. ADL	0.8 (6.9)
req. equality	1.8 (8.9)	max neg. per eff.	0.8 (6.1)
max pred. per eff.	1.8 (8.3)	min neg. per eff.	0.7 (8.0)
#types	1.6 (9.9)	#actions	0.7 (7.4)
min pred. per eff	1.6 (7.7)	#initial conditions	0.6 (7.0)
frac. actions w. neg. eff.	1.5 (9.8)	max pred. per pre.	0.5 (8.6)
req. STRIPS	1.5 (7.7)	mean pred. per pre.	0.4 (10.3)
req. typing	1.4 (8.1)	req action costs	0.2 (6.8)
mean params per pred.	1.4 (8.0)	#initial functions	0.1 (6.9)

Table 2: Mean coverage degradation and (in brackets) standard deviation (in %), over ten domain-preserving test folds, when ignoring a single group of highly correlated features of the FPDDL feature set for training a linear regression model without L1 regularization on the *binary* labels. Groups without performance degradation are omitted.

*error*. For the networks that predict the *binary* label we use the *Sigmoid* activation function and the *cross entropy loss*. In contrast to our linear regression and random forest models, our MLP technique learns a single model for planner selection.

**Model Evaluation** For training and evaluating models we split the tasks into groups of training and test tasks. Since neither linear regression nor random forests support validation data, we do not use validation data for the MLPs either. Because the range of some feature values varies greatly, we augment all feature sets by normalizing each feature to values between 0 and 1 and add these normalized features to the original feature sets. We only use the feature values of the training tasks to estimate the parameters for the normalization. We train the model to learn for each planner a function mapping from the features to a target function. To evaluate the final performance of the model on the test tasks, we use the model to predict the runtime for each planner on each test task, respectively their likelihood to solve the task. For each task we select the planner with the shortest runtime, respectively the highest likelihood. Afterwards, we count how many test tasks we would have solved with our decision. We note that our evaluation metric, which counts the solved tasks, differs from the training metric which optimizes a squared error, cross entropy, or the Gini score.

## Experiments

Our experiments are structured as follows. First, we evaluate how helpful simple machine learning techniques with explainable features are for selecting a planner that solves a given task. Then, we analyze which features are important for the models. Next, we inspect which planners are favored by our models. Afterwards, we train and visualize a decision tree for planner selection. Finally, we compare our models to Delfi1 (Katz et al. 2018), the winner of the IPC 2018, which uses convolutional neural networks for planner selection.

Usage	Cov <sub>P</sub>	Cov <sub>C</sub>	Planner
43.7	80.1	94.4	■ SymBA*
12.3	82.4	89.9	■ h2 + OSS + LM-Cut
9.7	78.7	54.5	■ h2 + DKS + iPDB
9.4	78.8	88.5	■ h2 + OSS + iPDB
8.1	82.7	78.1	■ h2 + DKS + LM-Cut
5.4	67.9	74.8	■ DKS + M&S-MIASM-DFP
3.3	74.8	97.5	■ h2 + DKS + M&S-BS-sbMIASM
2.8	65.9	86.6	■ h2 + OSS + M&S-SCC-DFP
2.1	75.8	100	■ h2 + DKS + M&S-BS-SCC-DFP
1.0	67.7	84.0	■ OSS + M&S-MIASM-DFP
0.8	72.2	75.0	■ h2 + OSS + M&S-BS-sbMIASM
0.7	68.4	6.2	■ h2 + DKS + ZO-PDB
0.4	67.6	60.0	■ h2 + DKS + M&S-SCC-DFP
0.2	68.6	100	■ h2 + OSS + ZO-PDB
0.1	62.3	100	■ h2 + DKS + Blind
0.0	62.5	–	■ h2 + OSS + Blind
0.0	75.2	–	■ h2 + OSS + M&S-BS-SCC-DFP

Table 3: Planners selected by the linear regression model without L1 regularization trained on the FPDDL features and optimizing the *binary* labels. The columns show how often each planner is chosen (in %), the coverage (in %) for the planner on all tasks (Cov<sub>P</sub>), and the coverage (in %) on tasks for which the model chooses the planner (Cov<sub>C</sub>).

All experiments — except for the comparison to Delfi1 — use 10-fold cross-validation, that is, we split the data into ten similarly-sized folds. We use one fold for testing and train the model on the other nine folds and repeat this procedure ten times. Each time a different fold is used for testing. The final performance is the mean performance over all ten runs. Cross-validation allows us to evaluate our approach on all benchmark tasks instead of just a subset (e.g., the tasks from the last IPC).

Planning tasks from the same benchmark domain share the same structure. Therefore, if the training and test data contain tasks from the same domain, the test performance does not show how well the model generalizes to new unseen tasks, but how well the model generalizes to tasks from known domains. Thus, we use *domain-preserving* splits, i.e., we ensure that all tasks of the same planning domain are assigned to the same data fold.

We run all experiments on single Intel Xeon Silver 4114 cores and limit memory usage to 3 GiB. All our data sets, code, and experiment results are published online (Ferber and Seipp 2022).

## Comparison of Machine Learning Models

We begin by evaluating how useful elementary machine learning techniques with basic features are at choosing a planner to solve a given task. For each of the four feature sets and each label representation (*binary*, *logtime*, and *time*), we train five linear regression configurations with L1 regularization weights from 0.0 to 5.0, a single random forest with 50 trees, and two neural network configurations with 3 resp. 5 hidden layers.

Table 1 shows the percentage of solved tasks for all models. A portfolio selector that chooses planners randomly obtains a coverage of 67.2%. We see that all models surpass this baseline. A portfolio selector that always chooses the planner with the highest coverage on the training set solves 73.5% of the test tasks. Almost all models surpass this stronger baseline. Although the models are not optimized for the coverage metric, the ability to predict the runtimes of a planner (resp. the likelihood of solving a task) helps to select a good planner for a task.

Averaging the mean coverage of our machine learning configurations over all feature sets and target functions reveals that the random forest is the most robust technique (81.9%). The next best configuration are MLPs with 3 layers with an average coverage of 81.5%. The most robust linear regression configuration uses no L1 regularization and solves 80.3% of the test tasks.

We observe a large standard deviation across all configurations. This stems from the fact that the data in the cross-validation folds is not *independent and identically distributed* (i.i.d.). If it were, the model would converge to a similar solution, regardless of which fold it is trained on. In our experiments, we split the data by domain to evaluate how the model performs on unknown domains. Thus, the training and test data can differ greatly.

Averaging over the feature sets and the machine learning configurations reveals how useful the different target functions are. Because we train five linear regression configurations, two MLP configurations, but only one random forest configuration, we weight the average. The *binary* labels are the least informative (80.0%). The *logtime* (81.5%) and the *time* (81.2%) labels are approximately equally informative. Although we only need to learn if a planner solves a given task, training the model to approximate planner runtime helps us to improve our planner selection.

The results also show that some of the strongest models use the FPDDL feature set, although all of its features are also contained in all other feature sets. The larger feature sets sometimes lead to lower coverage because they make it easier for the models to overfit on the training data. The linear regression models in particular, but also the MLPs suffer from overfitting: with growing feature sets, the training error decreases, but the test error increases.

## Feature Importance

Having trained well-performing models, now we analyze the importance of each feature. This shows which properties of a task are important for the runtime of a planner and allows us to skip unnecessary features to speed up the predictions.

To measure the importance of a feature  $A$ , we want to retrain the model without using  $A$ . Exploratory experiments showed that some groups of features are highly correlated (e.g., the number of PDDL objects and the number of equality conditions). If we excluded a single feature  $A$  but kept another feature  $B$  that is highly correlated with  $A$ , the model performance would be unaffected, because the model can use  $B$  instead of  $A$ . When we retrain the base model, we therefore exclude groups of correlated features. We put two features  $A$  and  $B$  into the same group if their absolute Pear-

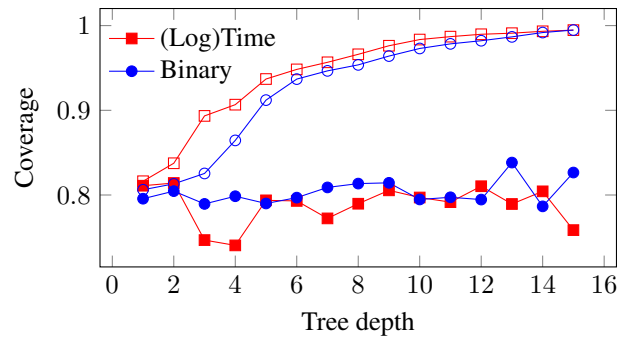


Figure 1: Mean coverage over all 10 domain-preserving folds on training (hollow) and test (filled) data using decision trees trained on binary (blue) and time/logtime labels (red) for increasing tree depth on the PDDL features.

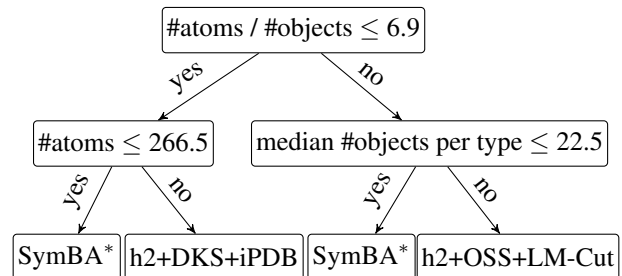


Figure 2: Example decision tree for one cross-validation fold. The decision tree uses *time* labels and has two layers.

son correlation is at least 0.95. This creates 47 feature groups for FPDDL and PDDL, 121 groups for FAWCETT, and 189 groups for the UNION feature set.

Table 2 shows the performance degradation of the best linear regression model for FPDDL features. The most important information for the model is whether the task requires negative preconditions: removing it degrades the performance by 4.4%. This suggests that some planners work better for tasks with negative preconditions than other planners. 21 out of 47 feature groups can be removed without a negative impact on the performance. Those 21 groups contain 22 features.

## Planner Selection

To understand how the models obtain high coverage scores, we examine which planners they choose and whether the models correctly learned when to choose them. Table 3 shows for the best linear regression model on the FPDDL feature set which planners are selected, how often those planners are selected, the coverage of those planners on all test tasks, and the coverage of those planners only on the tasks they have been chosen for.

We observe that the model almost always selects a planner from a group of planners with high coverage on the test task. Most often — for 43% of the tasks — it chooses SymBA\*, which is not the strongest planner, but almost solves as many tasks as the strongest one. Given this data, we could suspect

that the model just detected a group of good planners and randomly chooses one of them. We analyze in the following why this is not the case. If the model selected a planner for each task (weighted) randomly, then each individual planner would be used for a uniform subsample of the test tasks. Therefore, their coverage on their subsample would be approximately equivalent to their coverage on all test tasks. The linear regression model obtains for most planners a significantly better coverage on the tasks it assigns to them than the planners obtain on all test tasks. This shows that the model indeed learned when to use which planner.

### Single-Model Planner Selection

In the previous experiments, we used basic machine learning algorithms to learn models whose predictions can be easily interpreted. For example, the predictions of linear regression can be explained by multiplying the learned weights with the features of a task, then sorting those products (not the learned weights) by absolute magnitude and finally by comparing the positive and negative impact of the different features. However, our models make a prediction per planner, instead of choosing a planner directly. Therefore, their explanations answer the question “Why does the model think that planner  $A$  solves the given task?”, but not “Why is planner  $A$  preferable to planner  $B$ ?”. Models that answer the second question make it even easier to understand which planners work well for which tasks.

To obtain such a model we train a single decision tree using the planner names as training labels. A decision tree does not support multiple labels, i.e., planner names, for a single sample. Thus, we duplicate each training sample for each planner that solves it and assign one of the planner labels to each duplicate. Because this overrepresents frequently solved tasks, each duplicate is weighted by one over the number of times it was duplicated. This setup corresponds to the *binary* labels of previous experiments. To incorporate the *logtime* or *time* information into the training, we add an additional runtime factor to the weight of the duplicates. For two duplicates  $x$  and  $y$  where the planner for  $x$  is  $n$  times faster than the planner for  $y$ , the runtime factor for  $x$  is  $n$  times larger than the factor for  $y$  and for all duplicates that belong to the same task, the runtime factors sum up to one. This lets the decision tree prefer faster planners.

The result of the training procedure is a decision tree that directly predicts which planner to use for a given task. Obviously, the deeper the decision tree grows, the more questions it asks and each additional layer doubles the number of leaf nodes. Since using too many layers can lead to overfitting, we train decision trees with different depths and compare their performance with the same cross-validation procedure as above. Figure 1 shows the training (hollow) and test (filled) coverage of decision trees with increasing depth trained on the PDDL features. The coverage on the training data quickly approaches 100%, while the test coverage does not vary much for different tree depths. The trees obtained for the *time* and *logtime* labels are identical, so they share the same color in the plot.

Figure 2 illustrates how easy it is to interpret the learned decision trees. We show an exemplary decision tree with a

	FAWCETT			PDDL			Delfi Features		
Seconds	0.1	0.2	10.8	0.2	0.3	11.0	0.4	0.8	50.2
MiB	16	17	200	24	25	138	26	69	3023

Table 4: Minimum/mean/maximum time and memory usage to extract the features from the IPC 2018 tasks.

tree depth of 2 and *time*-weighted labels, because the tree has a good test performance and is small enough to be visualized. It reveals that SymBA\* is preferable to the other two planners in the tree only when the number of atoms and objects is small. The authors of SymBA\* confirmed that this aligns with their experience (personal communication).

### Comparison to Delfi1

In our final experiment, we compare our models against the strongest portfolio selector, Delfi1. Since for Delfi1 only the model and not the code is available, we cannot retrain it with cross-validation. Instead, we retrain the best configurations of our machine learning techniques (cf. Table 1) on the training data of Delfi1 ten times with different random seeds and evaluate all models on the tasks from the IPC 2018. For the single decision tree approach, we use the decision tree from Figure 2.

Delfi1 converts a given task to a graph and then to a raster image and finally passes this image to a CNN. In Table 4 we compare how computationally demanding these conversions are in comparison to computing the FAWCETT and PDDL features. On average, Delfi1 uses the most time and memory, but the mean resource requirements are small enough to be neglected for all three variants. However, on resource-constrained systems it might be problematic to run Delfi1 for the largest tasks.

Next, we compare the performance of the different models. Table 5 shows that all models significantly outperform the random baseline. Delfi1 performs best and solves 86.9% of the test tasks. However, our linear regression model performs almost equally well (86.2% coverage). The single decision tree also obtains a high coverage (82.7%). The random forest and the MLP solve many fewer tasks (76.8% and 70.8%). It is striking that the linear regression, decision tree, and random forest models have a standard deviation of 0.0. This is in contrast to Delfi1, whose authors note that they observed a high variance and that their retrained models did not reach the performance of the Delfi1 model that participated in the IPC 2018 (Sievers et al. 2019a).

For our models, the MLP requires the longest training time (111 seconds, single core). Similarly, training the Delfi1 models was a matter of minutes (personal communication with the authors). Evaluating the models requires roughly the same time and memory for all approaches. Overall, these resource requirements are negligible.<sup>1</sup>

The bottom half of Figure 3 shows the chosen planner for each pair of model and task, and whether this choice leads to solving the task. Delfi1 solves the most tasks, but in many

<sup>1</sup>All variants use Python for training and evaluation, which needs ~3.5s just to load the Tensorflow and scikit-learn packages.

	Random	Linear Regression	MLP	Random Forest	Decision Tree	Delfi1/CNN
coverage in %	60.6 (0.3)	86.2 (0.0)	70.8 (9.0)	76.8 (0.0)	82.7 (0.0)	86.9 (N/A)
training time in seconds	0	0.0 (0.0)	111.1 (16.8)	37.0 (6.1)	0.5 (0.1)	<3600 (N/A)
selection time in seconds	0	3.8 (0.2)	3.9 (0.1)	4.1 (0.3)	4.6 (0.4)	3.7 (0.4)
selection memory in MB	0	275.9 (434.0)	286.9 (131)	323.2 (110.3)	245.1 (23.5)	313.7 (0.2)

Table 5: For the best variant of each basic machine learning technique (cf. Table 1), the decision tree from Figure 2, and Delfi1, we show mean coverage, training time, and the runtime and memory usage for a single prediction on the IPC 2018 tasks. The numbers in brackets show standard deviation.

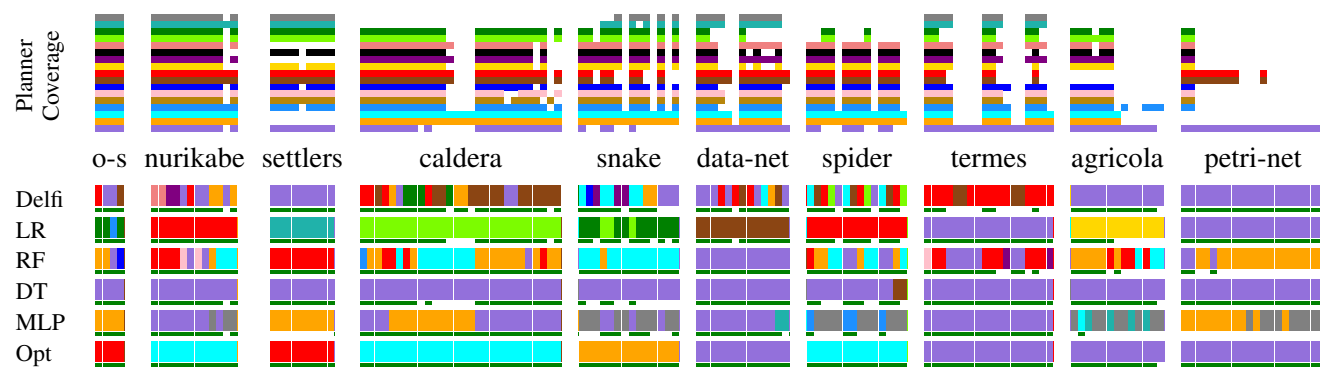


Figure 3: (Top) Each row indicates for a different planner which tasks of the test set it solved. The tasks are grouped by domain. The domains are sorted by average coverage. (Bottom) Each row indicates the planner chosen by the models of Table 5. Additionally, the green bar indicates whether the chosen planner solves the task. The last row (Opt) selects for each domain the planner with the highest coverage in that domain. If there is a tie, we choose the planner with the smaller cumulative runtime. Table 3 shows the mapping from planners to colors. We abbreviate the organic-synthesis domain with “o-s”.

domains it uses multiple planners. This suggests that Delfi1 does not base its decisions on common structures within a domain. Due to the black-box nature of the model of Delfi1, it is not easily possible to infer what it learns.

In contrast, the linear regression model clearly learns to assign planners to domains. Only twice it selects two different planners for a domain. Intuitively, it makes sense to learn to identify domains and which planner is good for a domain. To confirm our intuition, the last row *Opt* shows an oracle that selects for each domain the planner with the highest coverage in that domain. Indeed, we see that selecting a single planner per domain solves all but one test task. These findings align with an earlier empirical analysis by Roberts et al. (2008) who showed that it is both possible and beneficial for machine learning models to identify domains.

The random forest model also obtains high coverage on the IPC 2018 tasks. In most domains it solves more tasks than the linear regression. Its worse overall performance is mostly due to difficulties in the petri-net domain. The decision tree model almost always selects SymBA\* which is the planner with the highest coverage on the test tasks. This is more impressive than it sounds, because SymBA\* is not the best planner for the training tasks.

The MLP surpasses the random baseline, but has the lowest coverage of all models. Again, we clearly see the domains where it makes wrong predictions. In three out of ten domains it solves only one task and in two domains only half

of the tasks. In all other domains it solves almost all tasks.

The top half of Figure 3 shows that there are many tasks which are solved by almost all planners and many tasks that are solved by almost no planner. Obviously, selecting a good planner is much more important for hard tasks. If we check where the models, including Delfi1, fail to select a solving planner, we see that this often happens for tasks that are solved by almost no planner. An extreme case can be seen for the linear regression model in agricola. The model selects a single planner for the domain and solves half of the tasks. This sounds fine until we notice that those tasks are solved by most planners. Therefore, focusing on hard tasks could improve future models.

## Conclusions

We showed that simple and explainable machine learning techniques like linear regression produce strong portfolio selectors. Our simple linear regression model solves roughly the same number of tasks as Delfi1, the state of the art for planner selection. In addition to obtaining high coverage scores, the linear regression model is easy to interpret and fast to train and evaluate. We also analyzed which features are important for planner selection and presented how a single decision tree can be used to directly predict a planner and showed that such a tree can visualize how the model makes decisions.

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