

# Gray-Box Models for Performance Assessment of Spark Applications

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Keywords: Spark, Big Data, Machine Learning.

Abstract: Big data applications are among the most suitable applications to be executed on cluster resources because of their high requirements of computational power and data storage. Correctly sizing the resources devoted to their execution does not guarantee they will be executed as expected. Nevertheless, their execution can be affected by perturbations which can change the expected execution time. Identifying when these types of issue occurred by comparing their actual execution time with the expected one is mandatory to identify potentially critical situations and to take the appropriate steps to prevent them. To fulfill this objective, accurate estimates are necessary. In this paper, machine learning techniques coupled with a posteriori knowledge are exploited to build performance estimation models. Experimental results show how the models built with the proposed approach are able to outperform a reference state-of-the-art method (i.e., Ernest method), reducing in some scenarios the error from the 221.09-167.07% to 13.15-30.58%.

## 1 INTRODUCTION

Many factors such as multi-tenancy, virtualization and resource sharing can affect the performance of federated cloud services and their resources. Monitoring the status of the system during the applications runs to detect anomalies and perturbations can be complex and can further degrade the overall performance of the system. If the expected execution time of the running applications was known a priori, the identification of perturbed runs would be trivial since it would just be a matter of comparing real and expected execution time. In most of the scenarios of practical interest, however, even the expected execution time of running without perturbation can be unavailable. For this reason, performance modeling is used (Lazowska et al., 1984) to predict the performance of a real application by abstracting its behaviour.

Three main approaches have been proposed, namely, white-box analytical models (AMs), black-box machine learning (ML) models, and gray-box

ML models. AMs require the knowledge of the system internals, which is not always available and typically relies on some simplifying assumptions at the expense of losing accuracy (Lazowska et al., 1984). On the other side, black-box models (Didona and Romano, 2015) based on ML try to learn from data and make predictions without a detailed knowledge of the system. Finally, gray-box models combine aspects of the two approaches and consist of black-box models enriched with a set of features which better capture the behaviour of the applications under analysis. ML models require a training phase in which they use experimental data coming from different workloads and configurations. In order to obtain these initial data, it is necessary to run a set of experiments which is costly and time consuming. Moreover, since ML models are usually characterized by a wide set of hyper-parameters, which influence their accuracy, training should be done with hyper-parameter tuning to achieve the best possible results. Therefore, the training phase might take a long time. However, once trained, the prediction of ML models is very fast and usually very accurate. This is why ML models are recently becoming popular in studying the performance of large systems (Ataie et al., 2016).

In this paper, five classic ML models for regression are considered:  $\ell_1$ -regularized Linear Regression

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(LASSO), Neural Network, Decision Tree, Random Forests, and Support Vector Regression. A ML library was also developed in order to automate the training and evaluation of ML models and their hyper-parameter tuning. We focus on assessing Spark applications performance, i.e., evaluate the execution time measured for an application with respect to the expected one. Since the analysis is performed at the end of applications execution, a posteriori knowledge about them can be exploited. Examples of such type of information are number of tasks, maximum and average task execution time, shuffle time and number of bytes transmitted among the stages. To prove the generality of the proposed approach, a heterogeneous set of applications including Spark SQL-based applications and ML benchmarks was considered.

The results of our experiments showed that there is no single ML model which always performs well or which always outperforms the others. According to the initial application profiling data available in the training set and the application data size, different ML models provide significantly different accuracy. Therefore, it is very important to have a library to automate the training and hyper-parameter tuning process. In this way, different scenarios can be effectively investigated.

The rest of the paper is organized as follows. Section 2 presents the related work while Section 3 presents the evaluated performance models. The experimental setup is introduced in Section 4 and the obtained results are presented in Section 5. Finally, the conclusions are drawn in Section 6.

## 2 RELATED WORK

The performance analysis and prediction of big data applications running on the cloud can be tackled from different perspectives. The most traditional ones rely on analytical models (Nelson and Tantawi, 1988; Mak and Lundstrom, 1990; Tripathi and Liang, 2000; Ardagna et al., 2018) and simulation (Bertoli et al., 2009; Wang and Khan, 2015). Yet, recent studies have employed supervised machine learning models for performance prediction (Venkataraman et al., 2016; Mustafa et al., 2018; Pan et al., 2017; Alipourfard et al., 2017), which is the focus of this paper. One such example is a regression model proposed by the Spark creators (Venkataraman et al., 2016). The model uses a reduced set of features, which are functions of the data set size and of the number of cores. The estimation of the model parameters was based on non-negative least squares.

Mustafa *et al.* (Mustafa et al., 2018) proposed a

prediction platform for Spark SQL queries and machine learning applications, which, similarly to our gray box models, also exploits features related to each stage of the Spark application. This implies the existence of previous knowledge of the application profile. However, some of these features (e.g., numbers of *nonShuffledRead*, *shuffledReadRecords* and *inputPartitions*<sup>1</sup>) are at a lower level compared to ours, and thus require a finer-grained analysis of the Spark log to be computed. The authors reported prediction errors of 10% for SQL queries and about 25% for machine learning jobs. As we will show, our approach achieves better accuracy, and our experimental design considers more recent Spark workloads, including deep learning use cases.

CherryPick (Alipourfard et al., 2017) is a system that leverages Bayesian optimization to find near-optimal cloud configurations that minimize cloud usage costs for MapReduce and Spark applications. Unlike other studies, the goal was not to accurately predict applications performance, but rather design a model that is accurate enough to distinguish the best configuration from the rest. Similar ideas were also exploited in the design of Hemingway (Pan et al., 2017), which embeds the *Ernest* model and is specialized in the identification of the optimal cluster configuration for Spark MLlib based applications.

In a related, but different direction, Nguyen *et al.* (Nguyen et al., 2018) proposed a strategy to generate training data to fit a performance model. The model is meant to be used for predicting which Spark settings yield the smallest application execution time (i.e., capacity planning). In contrast, we here compare alternative ML models and feature sets in the task of predicting the performance of an application running on a given configuration.

## 3 ML MODELS FOR ASSESSING THE PERFORMANCE OF SPARK APPLICATIONS

This section presents the input features and the techniques used to build the proposed regression models, comparing them to the considered reference, model *Ernest* (Venkataraman et al., 2016). The performance models, which are built by means of Machine Learning (ML) techniques, consist of functions that relate application characteristics, infrastructure settings, and profiling information to the expected application execution time. The purpose of these models in the con-

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<sup>1</sup><https://spark.apache.org/docs/latest/rdd-programming-guide.html>

sidered context is to assess the trustworthiness and the absence of perturbations of the infrastructure w.r.t. the execution performance. More precisely, the aim is to determine whether an application run was affected by performance degradation due to resource contention. This task, which will be referred as *Performance Assessment* is of paramount importance in cloud management to verify that the resource allocation and isolation did not lead, because of multiple applications interference, to performance degradation. A second possible task can be the capacity planning, i.e., to determine the minimum amount of resources that must be allocated so that the execution time is smaller than a given limit. Differently from the first task, the second cannot rely on a posteriori knowledge and it will not be considered in the rest of the paper.

The type of data available for fitting the ML models depends on: (i) the application and (ii) the infrastructure settings. In this paper, three possible classes of Spark applications are considered: SQL based workloads, traditional machine learning algorithms, and SparkDL (Deep Learning pipelines for Spark).

### 3.1 Models Overview

Five classic ML models for regression are considered:  $\ell_1$ -regularized Linear Regression (LASSO), Neural Network, Decision Tree, Random Forests, and Support Vector Regression. A short description of each model is provided below.

- Linear regression (LR) assumes a linear relationship between features and the outcome. This model is typically fit using variants of the least squares method. The  $\ell_1$ -regularized and  $\ell_2$ -regularized Linear Regression are respectively known as LASSO, and Ridge Regression. It is possible to force all coefficients associated with features to be positive by fitting the data using the non-negative least squares (NNLS) method. In this paper, LASSO is considered which also helps in reducing the number of features by frequently setting weights to zero<sup>2</sup>. The NNLS method is used by the reference method (Ernest (Venkataraman et al., 2016)).
- Decision tree (DT) is a model represented a rooted, binary tree, composed of internal and leaf nodes. Each internal node represents a test based on the value of a feature. Leaf nodes aggregate training data that satisfy the tests encoded by the respective path. Algorithms used for constructing such a tree include ID3 (Iterative Dichotomiser),

C4.5 (a successor of ID3) and CART (Classification and Regression trees). Given a set of feature values, a prediction is made by applying successive tests until a leaf is reached. The prediction combines the outcome values associated with that leaf.

- Random forest (RF) is an ensemble method, which builds a collection of decision trees, to get more accurate and less variable results. Each tree is constructed by a random selection of features. The predicted outcome is obtained by averaging the predictions of all trees. Both fitting and prediction are efficient (computationally simple) for this method.
- Neural network (NN) is a model represented by a set of connected input/output units (nodes) in which each connection has a weight associated with it. The network consists of an input layer, one or more hidden layers and an output layer. The inputs are given to the input layer, then weighted and fed to the second layer which is a hidden layer. The outputs of a hidden layer can be given to another hidden layer or to the output layer. Finally, the output layer gives the prediction of the network for the given inputs. During the network training, the difference between predicted value and true value (error) will be propagated backward by apportioning them to each node's weights according to the amount of this error the node accounts for. This algorithm is called backpropagation.
- Support vector regression (SVR) is a two step model derived from support vector machines. First step aims at addressing non-linearities: a non-linear function is used to map original data in a high dimensional feature space. In the second step, hyper-planes are used to describe the linear functions between points in the created space and the metric to be estimated.

Linear regression was chosen because of its readability and its usage in the Ernest models. Decision trees and random forests while still partially interpretable, are also able to describe non-linear relationships in the data. Last, support vector regression and neural networks are able to capture quite complex relationships between applications characteristics and their execution time.

### 3.2 Features Overview

Table 1 shows the features used by the considered models. Two sets of features can be identified: features which are available *a priori* and features which

<sup>2</sup><https://web.stanford.edu/~hastie/ElemStatLearn/>

Table 1: Features used in models for performance assessment.

| Type of Knowledge      | Features  |
|------------------------|---|
| A Priori               | <ul style="list-style-type: none"> <li>- Ratio of data size to number of cores</li> <li>- Log of number of cores</li> <li>- Data size</li> <li>- Number of cores</li> <li>- Number of TensorFlow cores (SparkDL only)</li> </ul>  |
| A Posteriori           | <ul style="list-style-type: none"> <li>- number of tasks</li> <li>- max/avg time over tasks</li> <li>- max/avg shuffle time</li> <li>- max/avg number of bytes transmitted between stages</li> <li>- number of executor cores</li> <li>- inverse of number of executor cores</li> </ul> |
| A Posteriori (SparkDL) | <ul style="list-style-type: none"> <li>- individual TensorFlow calls execution time</li> <li>- inverse of total number of cores</li> </ul>  |

are only available *a posteriori*. The former set is composed of features which are derived by the Ernest model and exploit information which is available before running the applications (more precisely, the number of cores and the input data size). The latter set is composed of features which are associated with the Spark DAG (directed acyclic graph), which represents the sequence of stages executed by Spark when running an application<sup>3</sup>. This type of information can be easily extracted from applications logs after their completion. In general, since the DAG is specific to each application run, the relationship between these metrics and running time only holds for the same DAG. To be able to achieve this, a fixed DAG structure was needed, at least across different number of cores. In particular, for each stage, the extracted information is: the number of tasks, the maximum and average execution time of the tasks, the maximum and the average shuffle time, the maximum and average number of bytes transmitted among the stages. For SparkDL, not only the cores assigned to Spark executors, but also the TensorFlow execution time and the inverse of total number of cores available in the cluster are included as features.

It is worth noting that full information (i.e., including a posteriori knowledge) can be used since built models are used to assess the performance of the applications and not to predict it.

## 4 EXPERIMENTAL SETTINGS

This section presents and details the experimental setup adopted in all the experiments performed to collect the results presented in this paper. This section first describe the applications used as workloads in our experiments (Section 4.1) and the considered tar-

<sup>3</sup><https://data-flair.training/blogs/dag-in-apache-spark/>

get platforms on which applications were run (Section 4.2). How the data were split into training and test sets is described in Section 4.3, while the model parametrization is presented in Section 4.4. Finally the metrics adopted to evaluate the models are described in Section 4.5.

### 4.1 Applications Workloads

To verify the generality of the proposed approach, three different types of applications are considered, which are representatives of different types of workloads:

- Query26, an interactive query from the TPC-DS industry benchmark<sup>4</sup> representative of SQL-like workload, which includes a small number of tasks and stages (i.e., 10). It was run for various input data set sizes: 250 GB, 750 GB, and 1000 GB.
- K-means, a ML benchmark from Sparkbench<sup>5</sup>. K-means is the core of many ML applications (clustering is an unsupervised learning technique, which, however, is used very frequently to perform preliminary data set analyses even if in the following classification techniques are considered). It was run for Spark dataframes with 100 features, with values uniformly distributed in the [0,1] range and the number of rows varying in 5, 10, 15 and 20 million. The DAG was the same across all runs and for all the data sizes, containing 15 stages.
- Image classification, a benchmark for image processing internally developed and based on the SparkDL library<sup>6</sup>. The developed application is based on the novel deep learning pipelines which

<sup>4</sup><http://www.tpc.org/tpcds>

<sup>5</sup><https://codait.github.io/spark-bench>

<sup>6</sup><https://databricks.github.io/spark-deep-learning/site/index.html>

makes possible to develop high-level deep learning applications on Spark. In particular, this framework supports transfer learning, one of the most popular approaches used in the deep learning when the data set for training is small (Csurka, 2017), which enables to use pre-trained models on different tasks. In particular, the application we developed is a binary image classification using *InceptionV3* as featurizer and *linear SVM* as classifier. The number of images in the input varied in 1000, 1500 and 2500 while the number of stages is 8. As anticipated in Section 3.2, this benchmark is characterized by additional features and, hence, is the most complex of the three considered workloads. SparkDL heavily relies on TensorFlow which affects the application completion times. When SparkDL runs, the number of cores allocated to Spark workers can be limited, but *spark-submit* parameters cannot control the number of cores for TensorFlow, which uses all the cores available in the cluster. For this reason, also the TensorFlow number of cores (which corresponds to the number of cores available in the cluster) and its inverse are included in the set of used features.

## 4.2 Hosting Platforms

Applications were run on two platforms, Microsoft Azure and a private IBM Power8 cluster, which are representatives of different computing environments. As a public cloud, Microsoft Azure is potentially affected by resource contention. Thus, application executions might experience more variability. In contrast, IBM Power8 was fully dedicated to run the considered benchmarks without any other concurrent activity (thus with no resource contention).

Query 26 and SparkDL were executed on Microsoft Azure using the HDInsight service with workers based on 6 D13v2 virtual machines (VMs), each with 8 CPU cores and 56 GB of memory running Spark 2.2.0 on Linux. SparkDL application requires, in addition, that TensorFlow and Keras are available on the Spark cluster: versions 1.4.0 and 2.1.5 were used, respectively. The executors memory was set to 10 GB. K-means was run on a Power8 deployment that includes Hortonworks distribution 2.6, same as Microsoft Azure, with 4 VMs, each with 12 cores and 58 GB of RAM, for a total of 48 CPU cores available for Spark workers, plus a master node with 4 cores and 48 GB of RAM. The executors memory, in this case, was set to 4GB.

For Query 26 and K-means, experiments were run varying the number of Spark cores between 6 and

44 cores (step of 2), repeating the execution with the same configuration 6 times. For SparkDL, the number of cores was varied between 2 and 48 (step of 2), repeating each experiment with the same configuration (i.e., the number of images and cores) 5 times. By considering different workloads, hosting platforms and setup configurations, we build a rich set of scenarios to test our prediction models.

## 4.3 Train and Test Sets Settings

Table 2: Workload data sizes in different scenarios.

| Workload         | Core Interpolation |      | Data Extrapolation |      |
|------------------|--------------------|------|--------------------|------|
|                  | Training           | Test | Training           | Test |
| Query 26 [GB]    | 750                | 750  | 250, 750           | 1000 |
| K-means [Rows]   | 15                 | 15   | 5, 10, 15          | 20   |
| SparkDL [Images] | 1500               | 1500 | 1000, 1500         | 2000 |

To evaluate the ML models accuracy and analyze their interpolation and extrapolation capabilities, the data are split into training and test sets according to the data size and by considering different cores configuration. For each workload, in particular, two different types of scenarios are considered, which are summarized in Table 2

- *core interpolation* scenarios: only runs with the same dataset size are considered (reported in Table 2). Figure 1 shows the various scenarios (y-axis) built for each workload based on different splits of the data into training and test sets: in each row (case number), blue boxes represent configurations for which the data were used as part of the training set (and cross-validation) and red crosses indicate configurations used as part of the test set<sup>7</sup>.
- *data size extrapolation* scenarios: the runs with the largest dataset size (spanning across all available cores configurations) are put in the test set while the runs with the other dataset sizes in the training data, as shown in the two rightmost columns of Table 2.

In the first class of scenarios, the cases were designed such that larger case numbers are associated with harder predictions, as there training data include samples from a smaller range of experiments w.r.t. the number of cores. For example, for both Query 26 and K-means, scenario C1 is built by alternating configurations in the sequence of the number of cores (x-axis) as training and test data. For Query 26, data from experiments with the number of cores equal to 6, 10, ..., 40 and 44 are put in the training data (blue boxes)

<sup>7</sup>The experiments with Query 26 on 20 cores were removed because of anomalies (see Figure 1a).

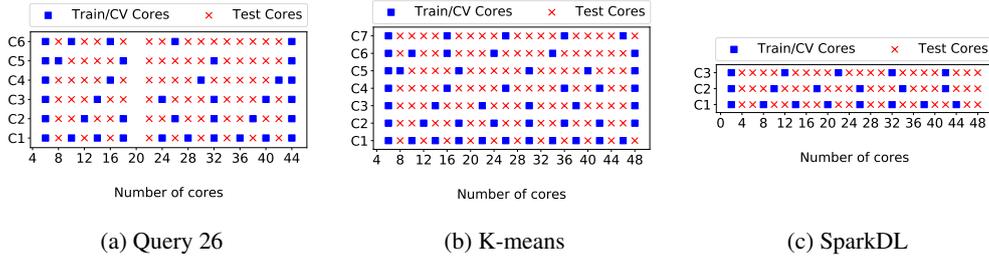


Figure 1: Core interpolation scenario: train-test split in each case for Query 26, K-means and SparkDL.

while the remaining samples are included in the test set (red cross). The gap between the number of cores of consecutive configurations included in the training data is gradually incremented. The gap in cases 4, 5, 6, and 7 was varied to assess its impact on model accuracy. Since there is a large difference in the application completion time in the runs where the number of cores is small, the data for the smallest number of cores were always included in the training set. For SparkDL, the process was the same but limiting the number of cases to three.

Even in the second class of scenarios, the training sets are further reduced by removing runs with some configurations of number of cores according to the same schema presented for core interpolation. By doing so, in these experiments the core interpolation and the data size extrapolation capabilities are evaluated at the same time. In other words, the data size extrapolation differ from the core interpolation scenarios because: (i) the dataset sizes in training and test sets are no longer the same, (ii) the test set also includes observations where the number of cores is the same as in some observations of the training set (but again with different dataset sizes).

#### 4.4 Hyper-parameter Tuning

Each of the model described in Section 3.1 is characterized by a set of hyper-parameters which can be tuned to improve the accuracy of the models. Correctly sizing the design space on them is a critical task, since a too narrow solution space can exclude good solutions, while on the contrary a too wide solutions space can lengthen too much the model selection process. The hyper-parameters and the values which were considered in this work are listed in Table 3. An inhouse Python library was developed on the top of PyTorch 0.4.0<sup>8</sup> (for neural network training) and of scikit-learn 0.19.1<sup>9</sup> (for all the other techniques) to explore their different values. For every algorithm, the Mean Squared Error (MSE) integrated with *hold-*

*out* cross-validation was used to select the values that led to the best model.

To further prevent over-fitting, a regularization term is added to LR (Linear Regression) and NN (Neural Network). For LR, LASSO was chosen providing  $\ell_1$ -norm. The use of intercept and the penalty constant  $\alpha$  are the set of available hyper-parameters and are shown in Table 3 For the NN algorithm, the

Table 3: Hyper-parameters for ML techniques.

| Linear Regression             |   |                     |
|-------------------------------|---|---------------------|
| Hyper-Parameter               | Values                                      |                     |
| Penalty $\alpha$              | 0.001, 0.01, 0.05, 0.1, 0.5, 1.0, 5.0, 10.0 |                     |
| Fit intercept                 | True, False                                 |                     |
| Neural Network                |   |                     |
| Hyper-Parameter               | Values                                      |                     |
| # Layers $n$                  | 1, 2, 3                                     |                     |
| # Perceptrons/Layer           | all combinations in $[3, 4, 5]^n$           |                     |
| Activation Functions          | sigmoid, ReLU, tanh                         |                     |
| $\ell_2$ Penalty              | 0.0001, 0.001, 0.01, 0.05, 0.1              |                     |
| Learning Rate                 | 0.001, 0.01, 0.1                            |                     |
| $\beta_1$                     | 0.7, 0.8, 0.9                               |                     |
| # Minibatches                 | 1   |                     |
| Optimizer                     | Adam, SGD                                   |                     |
| Decision Tree & Random Forest |   |                     |
| Hyper-Parameter               | Decision Tree                               | Random Forest       |
| Max Depth                     | 3, 5, 10, No Limit                          | 3, 10, 20, No Limit |
| Max Features                  | auto, sqrt, log                             | auto, sqrt, log     |
| Min samples to split          | 2.0   | 2.0                 |
| Min samples per leaf          | 1%, 5%, 10%, 20%, 30%                       | 1, 2, 4             |
| Criterion                     | MSE, fMSE, MAE                              | MSE, MAE            |
| # Trees                       | NA  | 5, 10, 50, 100      |
| SVR                           |   |                     |
| Hyper-Parameter               | Values                                      |                     |
| C                             | 0.001, 0.01, 0.1, 1, 10, 50, 75             |                     |
| $\epsilon$                    | 0.05, 0.1, 0.2, 0.3, 0.5                    |                     |
| $\gamma$                      | 1e-7, 1e-4, 0.001, 0.01, 0.1, 1             |                     |
| Kernel                        | linear, rbf, polynomial, sigmoid            |                     |
| Degree                        | 2, 3, 5, 7                                  |                     |

$\ell_2$  penalty Frobenius norm (Golub and Van Loan, 1996) was used. Also rectified linear unit function *ReLU* was selected in general as the best activation function. In all cases, the training data size was not large; therefore, we set the number of minibatches to 1 in order to consume the whole input at once. The main hyper-parameter considered to evaluate the performance was the optimizer. *Adam* and *Stochastic Gradient Descent (SGD)* were evaluated as possible candidates.

The former was selected as our experiments showed that it converges much faster than the latter. The number of epochs was set to 10,000. DT and RF share many hyper-parameters and their values, there-

<sup>8</sup><https://pytorch.org>

<sup>9</sup><https://scikit-learn.org>

fore, are grouped in Table 3. *Max Depth* is the maximum depth of the tree which is specified to avoid over-fitting. *Max Features* is used to select the number of available features to consider when searching for the best split. A value of *auto* implies a maximum number of features equal to the total number of features. Values of *sqrt* and *log* imply a maximum equal to the square root and the base-2 logarithm of the number of features, respectively. *Minimum Samples to Split/per Leaf* is used for setting, respectively, the minimum number of samples required to split a node and the minimum percentage/number of samples required to be a leaf. *Criterion* is the function used to measure the quality of a split: *MSE* stands for mean square error (minimizes  $\ell_2$  loss), *fMSE* stands for mean squared error with Friedman’s improvement score for potential splits and, last, *MAE* stands for mean absolute error (minimizes  $\ell_1$  loss). Parameter *number of trees*, the number of trees in the forest, only applies to RF. A range of values is explored to analyze diminishing return effects on the error. Finally, concerning the SVR hyper-parameters, the degree is used only with the polynomial kernel while the gamma parameter is valid only for polynomial, rbf and sigmoid kernel. In the case of this regression technique, different types of kernels are tried to observe which would capture better the behavior of the application time according to the number of cores.

#### 4.5 Performance Metrics

To be able to compare the performance results of different methods, the mean absolute percent error (MAPE) of the response time assessment was used, as it is more widely used in the performance literature (Lazowska et al., 1984) than MSE (used for hyper-parameter tuning). Moreover, the results across different experiments can be easily integrated even if they have very different execution times. Indeed, MAPE measures the relative error (in absolute terms) of the prediction with respect to the true response times, i.e.,

$$MAPE = \frac{100\%}{N} \sum_{k=1}^N \left| \frac{y_k - \hat{y}_k}{y_k} \right| \quad (1)$$

where

- $N$  is the number of data points.
- $y_k$  is the response time measured on the operational system.
- $\hat{y}_k$  is the predicted response time from the learnt model.

For each setup, 10 runs were executed for the LR, DT and RF algorithms, and the average MAPE across

all 10 runs was computed and reported. For NN, which has much longer training times, we performed a single run (i.e., random train-test split).

## 5 EXPERIMENTAL RESULTS

In this section, the prediction results for each workload on each sets of scenarios (i.e., *core interpolation* and *data extrapolation*) are presented. For each set, this section reports the results in terms of MAPE for each case described in Section 4.3 for each of the ML technique described in Section 3.1 (LR, NN, DT, RF, and SVR) comparing them with the reference model (Ernest).

### 5.1 Query 26 Results

Table 4 and Table 5 show the MAPE results for core interpolation and data extrapolation scenarios, respectively, for Query 26. It is worth noting that in both the sets of scenarios, Ernest method is quite accurate (worst error is 8.02%) and outperforms gray box models since the features it exploits are better able to capture the characteristics of the application in terms of performance. Moreover, there is no significant differences in its accuracy across different cases, showing that even with few observations it is possible to obtain good fits.

Analyzing the results of the gray-box models, there is no ML technique which always outperforms the other, but LR and NN are the best choices depending on the particular scenario.

Table 4: MAPE (%) of execution time estimates on Power8 for Query 26 in core interpolation scenario (fixed data size of 750 GB for all data sets).

|    | Ernest      | Gray Box |       |      |       |       |
|----|-------------|----------|-------|------|-------|-------|
|    |             | DT       | LR    | NN   | RF    | SVR   |
| C1 | <b>1.50</b> | 9.64     | 4.46  | 7.10 | 6.71  | 7.35  |
| C2 | <b>1.64</b> | 9.92     | 8.82  | 5.57 | 12.32 | 20.53 |
| C3 | <b>1.71</b> | 16.12    | 6.23  | 4.24 | 15.31 | 10.25 |
| C4 | <b>1.66</b> | 27.05    | 10.62 | 6.09 | 14.37 | 16.92 |
| C5 | <b>1.59</b> | 25.54    | 42.08 | 6.23 | 44.60 | 39.74 |
| C6 | <b>1.70</b> | 11.39    | 35.80 | 6.75 | 41.44 | 68.95 |

Even if they are not able to achieve the same accuracy of the Ernest method, the worst result (32.29% on C4 of data extrapolation scenario) still allows to assess the performance of the run application

### 5.2 K-means Results

Table 6 and Table 7 present the result obtained by Ernest and by the ML techniques on K-means. Dif-

Table 5: MAPE (%) of execution time estimates on Power8 for Query 26 in data extrapolation scenario (250 GB, 750GB for training and 1000GB for testing).

|    | Ernest      | Gray Box |       |       |       |       |
|----|-------------|----------|-------|-------|-------|-------|
|    |             | DT       | LR    | NN    | RF    | SVR   |
| C1 | <b>7.49</b> | 37.13    | 32.91 | 10.23 | 44.16 | 38.08 |
| C2 | <b>7.44</b> | 35.01    | 27.26 | 36.07 | 40.66 | 32.30 |
| C3 | <b>7.31</b> | 32.39    | 36.36 | 20.18 | 47.46 | 38.74 |
| C4 | <b>7.26</b> | 32.75    | 32.29 | 48.80 | 46.29 | 32.31 |
| C5 | <b>7.59</b> | 41.93    | 12.41 | 21.90 | 31.50 | 18.11 |
| C6 | <b>8.02</b> | 38.45    | 24.05 | 19.91 | 32.22 | 29.22 |

Table 6: MAPE (%) of execution time estimates on Power8 for K-means in core interpolation scenario (15M points for training and 15M points for test).

|    | Ernest | Gray Box     |        |              |        |              |
|----|--------|--------------|--------|--------------|--------|--------------|
|    |        | DT           | LR     | NN           | RF     | SVR          |
| C1 | 126.69 | 17.27        | 74.04  | <b>11.99</b> | 105.31 | 28.09        |
| C2 | 148.10 | 21.41        | 83.33  | <b>10.27</b> | 112.77 | 29.13        |
| C3 | 161.35 | 46.46        | 122.07 | 47.30        | 67.58  | <b>36.14</b> |
| C4 | 176.52 | 49.66        | 143.33 | 47.60        | 81.70  | <b>24.47</b> |
| C5 | 187.00 | 31.20        | 273.19 | <b>29.88</b> | 99.74  | 84.00        |
| C6 | 159.88 | <b>21.90</b> | 166.57 | 26.66        | 59.40  | 66.75        |
| C7 | 178.08 | <b>31.59</b> | 159.44 | 47.65        | 102.96 | 38.74        |

Table 7: MAPE (%) of execution time estimates on Power8 for K-means in data extrapolation scenario (5M, 10M, and 15M points for training and 20M points for test).

|    | Ernest | Gray Box     |              |              |       |              |
|----|--------|--------------|--------------|--------------|-------|--------------|
|    |        | DT           | LR           | NN           | RF    | SVR          |
| C1 | 167.07 | 26.47        | 20.24        | 59.50        | 26.07 | <b>16.04</b> |
| C2 | 183.09 | 26.31        | <b>13.15</b> | 91.60        | 29.19 | 18.63        |
| C3 | 200.83 | 37.28        | 31.86        | 131.54       | 33.47 | <b>30.58</b> |
| C4 | 204.42 | 69.61        | 24.24        | 453.67       | 32.08 | <b>18.67</b> |
| C5 | 221.09 | 26.89        | 26.86        | <b>16.01</b> | 39.72 | 25.29        |
| C6 | 206.59 | <b>21.19</b> | 37.72        | 37.39        | 29.61 | 34.16        |
| C7 | 208.37 | 29.44        | 43.14        | 145.81       | 30.21 | <b>24.06</b> |

ferently from the previous workload, the reference model here is not able to correctly describe the expected performance of the considered application. In the best case, the estimation error is 126.69% while in the worst case it reaches up to 221.09%. On the contrary, the errors of the best considered ML technique in each scenario are significantly smaller. In the worst case, C3 of core interpolation, the error of the best technique (i.e., SVR) is 36.14%. Even for this workload, there is no ML technique which always performs better than all the other in all the considered scenario. Indeed, all the techniques but RF are the best choice in at least one combination of case-scenario.

### 5.3 SparkDL Results

Finally, results for SparkDL are shown in Table 8 and Table 9 for the core interpolation and data extrapolation scenarios. Even if the predictions by the Ernest method for this workload are better than for the previous, it still outperformed by other ML techniques. In the core interpolation scenario the difference is not so relevant since the error of the Ernest prediction is in the range 5.71-10.48% while the error of the best ML technique is in the range 3.70-4.66%. As for previous workloads, there is not an absolute best technique: NN, SVR, LR get the best results in each of the three cases.

On the contrary, the data extrapolation for SparkDL results to be a harder scenario to be addressed by the Ernest method with MAPE in the range 36.81-43.49%. Proposed models produce a significantly smaller error (range is 9.90-10.04%). Even in this last scenario there is not a unique winner: LR is the best technique for C1 and C2 while the best C3 model is built by NN.

Table 8: MAPE (%) of execution time estimates on Microsoft Azure for SparkDL in core interpolation scenario (1500 images for training and 1500 images for testing).

|    | Ernest | Gray Box |             |             |      |             |
|----|--------|----------|-------------|-------------|------|-------------|
|    |        | DT       | LR          | NN          | RF   | SVR         |
| C1 | 10.48  | 5.16     | 5.60        | <b>3.84</b> | 5.87 | 4.12        |
| C2 | 6.30   | 5.67     | 9.47        | 11.32       | 5.56 | <b>4.66</b> |
| C3 | 5.71   | 6.40     | <b>3.70</b> | 5.07        | 8.29 | 4.96        |

Table 9: MAPE (%) of execution time estimates on Microsoft Azure for SparkDL in data extrapolation scenario (1000 and 1500 images for training and 2500 images for testing).

|    | Ernest | Gray Box |              |             |       |       |
|----|--------|----------|--------------|-------------|-------|-------|
|    |        | DT       | LR           | NN          | RF    | SVR   |
| C1 | 43.49  | 33.10    | <b>10.73</b> | 25.04       | 36.72 | 27.82 |
| C2 | 37.39  | 34.94    | <b>10.04</b> | 17.64       | 35.47 | 32.13 |
| C3 | 36.81  | 32.19    | 14.76        | <b>9.90</b> | 35.75 | 32.97 |

### 5.4 Discussion

The previous sections presented the results of the reference model and of the ML models for each analyzed workload and scenario. The Ernest models perform best (MAPE smaller than 8.02%) in the simplest considered scenario (i.e., Query 26 both in core interpolation and data extrapolation). In the SparkDL core interpolation scenario, Ernest models still perform well despite not being the best models. In contrast, in the other scenarios, the large MAPE values (up to 187%) make the models unsuitable for produc-

tion environments, thus justifying the necessity of introducing new techniques to be effectively exploited.

From the results previously presented, it can be noticed that there is not a unique ML technique which outperforms all the others in every situation. Moreover, even by limiting to a single type of scenarios there is not a single winner. On the contrary, a slight change in the composition of the training set and of the test set (i.e., considering different cases) may change which is the technique which performs best. For example, in the data extrapolation scenario for K-means the best technique is SVR for C1, C3, C4, and C7, LR for C2, NN for C5 and DT for C6.

The comparison between the best gray box models and the reference Ernest model leads to two different situations. In scenarios where applications are characterized by regularity (i.e., Query 26 and SparkDL with fixed data size), Ernest yields very good results with MAPE values smaller than 11%, whereas the best gray box model generally achieves worse performance (MAPE of best models is in the range 3.84-42.29%). Yet, in the remaining scenarios, which are characterized by a larger variability in the application execution times, the best gray box model outperforms the Ernest model by a large margin. The MAPE range of the latter is 36.81-187.0% while the largest error of the best gray box model is only 31.59% (C of core interpolation with K-means). However, recall that gray box models use DAG-related features which are not available for the test instance at prediction time (*a priori*), but they can be used as they are only to assess the performance of the analyzed applications.

## 6 CONCLUSIONS AND FUTURE WORK

In this paper, the accuracy of alternative supervised machine learning techniques to assess the performance of Spark applications has been analysed. Our aim is to train models able at identifying perturbations which affect the execution time of production applications. Experimental results on a rich set of different scenarios demonstrated that the proposed gray black box models are able to achieve relevant accuracy in different scenarios with different workloads. Moreover, in complex scenarios (i.e., data extrapolation in complex applications) where the Ernest reference model fails (error up to 187%), the largest error of the best gray-box model is 31.59%. However, results show how there is no ML technique which always outperforms the others, hence different techniques have to be evaluated in each scenario to choose the best model. As future work, the study of the

performance of Spark applications running on GPU-based clusters is foreseen. Moreover, the use of the models to identify resource contention on production systems will be also considered.

## ACKNOWLEDGEMENTS

This work has been partially supported by the project ATMOSPHERE (<https://atmosphere-eubrazil.eu>), funded by the Brazilian Ministry of Science, Technology and Innovation (Project 51119 - MCTI/RNP 4th Coordinated Call) and by the European Commission under the Cooperation Programme, Horizon 2020 (grant agreement no 777154).

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