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CP-based cloud workload annotation as a preprocessing for anomaly detection using deep neural networks

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Abstract. Over the last years, supervised learning has been a subject of great interest. However, in presence of unlabelled data, we face the problem of deep unsupervised learning. To overcome this issue in the context of anomaly detection in a cloud workload, we propose a method that relies on constraint programming (CP). After defining the notion of quasi-periodic extreme pattern in a time series, we propose an algorithm to acquire a CP model that is further used to annotate the cloud workload dataset. We finally propose a neural network model that learns from the annotated data to predict anomalies in a cloud workload. The relevance of the proposed method is shown by running simulations on real-world data traces and by comparing the accuracy of the predictions with those of a state of the art unsupervised learning algorithm.

1 Introduction

With the increase of the use of cloud computing technologies, more and more applications rely on a cloud infrastructure. This model is named Infrastructure as a Service (IaaS). Since failures are common in such large systems [21], the cloud provider needs to ensure the integrity of the infrastructure, prevent failures or fix them as soon as possible.

Most predictive machine learning algorithms rely on historical data to learn a predictive model that can predict the outcome of a given observation. Generally, cloud providers have large quantity of historical data obtained by monitoring some metrics. Such cloud workloads are modelled by time series that are generally not labelled. To address this issue, some data scientists require human intelligence through crowdsourcing services like Amazon Mechanical Turk [20, 17]. The drawback of such approach is its cost in time and money, and even more the reliability of the produced annotations [13]. In the absence of labels, the problem of deep unsupervised learning has been studied in [10]. Most of these approaches rely on k-means clustering [14]. As shown in Section 4.2, a clustering approach is not well suited for anomaly detection in the context of cloud workloads.

In this context, the contribution of this paper is twofold. First we introduce the generic notions of *extreme patterns* (i.e. pattern occurrences within a time

series for which one or several feature values take very small or very large values relatively to the rest of the time series), and of *quasi-periodic pattern group* within a time series. Second, we propose a three-step method to solve the problem of predicting malfunction in a cloud data centre infrastructure given its workload:

- Using the notion of *extreme patterns*, we first acquire a constraint programming (CP) model that is able to discriminate between a workload presenting a malfunction and one that does not.
- Then we use the acquired CP model to automatically label the historical workload dataset.
- Finally, we train a deep neural network to predict the malfunctions.

The rest of the paper is organised as follows. Section 2 provides the necessary background on time series in the context of constraint programming. Section 3 details our main contribution, namely the definition of *quasi-periodic extreme patterns* and the illustration how to use it to annotate cloud workloads. In Section 4, we present two methods, the first one based on supervised learning, and the second one based on unsupervised learning (through the k-means algorithm) to predict anomalies in a cloud workload. Finally, we evaluate and compare both models in Section 5 and conclude in Section 6.

2 Background

A *time series* is a sequence corresponding to measurements taken over time. We use time series to model resource production or consumption, e.g. energy, memory, cpu, bandwidth [6, 15]. These type of time series are constrained by physical or organizational (in general structural) limits as well as by business rules, which restrict the evolution of the series.

Definition 1 (signature). *Given a time series $x = x_1, x_2, \dots, x_n$, the signature of x is the sequence $s = s_1, s_2, \dots, s_{n-1}$, where every s_i is defined by $(x_i < x_{i+1} \Leftrightarrow s_i = '<')$ \wedge $(x_i = x_{i+1} \Leftrightarrow s_i = '=')$ \wedge $(x_i > x_{i+1} \Leftrightarrow s_i = '>')$.*

Definition 2 (s-occurrence, i-occurrence, e-occurrence, found index). *Consider a time series $x = x_1, x_2, \dots, x_n$, its signature sequence $s = s_1, s_2, \dots, s_{n-1}$, a regular expression σ over the alphabet $\{ '<', '=', '>' \}$, two natural numbers b and a , and a subsignature s_i, s_{i+1}, \dots, s_j with $1 \leq i \leq j \leq n-2$, forming a maximal word in s matching σ . The s-occurrence of σ is the index sequence i, \dots, j ; The i-occurrence of σ is the index sequence $i + b, \dots, j$; The e-occurrence of σ is the index sequence $i + b, \dots, j + 1 - a$; The found index is the smallest index k in the interval $[i, j]$ such that the word $s_i s_{i+1} \dots s_k$ is an occurrence of σ .*

An s-occurrence identifies a maximal occurrence of a pattern in a signature sequence, while an i-occurrence identifies a maximal occurrence of a pattern in an input sequence. Note that, by Definition 2, i-occurrences of the same pattern never overlap. The feature value of a pattern occurrence is computed from the e-occurrence, where the constants b and a are used for respectively trimming the left and the right borders of the regular expression σ .

3 Detection of quasi-periodic extreme patterns in CP

Houssam *et al.* present in [2] a formalisation of arrhythmia detection algorithms. Their algorithm relies on quantitative regular expressions [3] for peak detection. Scholkmann *et al.* [18] propose another parameter free algorithm for peak detection in periodic or quasi-periodic signals. While those algorithms are designed for peak detection only, our framework [5, 11] is compatible with a large class of regular expressions [11] and offers more than 700 time-series constraints [4].

First, since we aim at extracting relevant maximal occurrence of patterns, we formally define the notion of extreme pattern occurrences. Second, since we also aim at quantifying how regularly such maximal occurrence of patterns appear we define the notion of quasi-periodic extreme pattern. All the corresponding definitions will be illustrated on a concrete example at the end of this section.

3.1 Defining extreme pattern occurrences

In the same way we already synthesise a register automaton for computing the result associated with a time-series function, we also synthesise a register automaton for computing the feature values of each maximal occurrence of a given pattern in a time series in linear time wrt the time-series length. This will be used to extract the extreme feature value, a notion that we now define.

Definition 3 (extreme feature value of a pattern occurrence). *Given a regular expression σ , a feature f , a time series ts containing at least one maximal occurrence of σ , and a threshold $\tau \in [0, 1]$, the i^{th} maximal occurrence of σ within ts is extreme iff*

$$\begin{aligned} f_{\sigma}(i) &\in [\min_{f,\sigma}(ts), \min_{f,\sigma}(ts) + \tau \cdot \min_{f,\sigma}(ts)] \vee \\ f_{\sigma}(i) &\in [\max_{f,\sigma}(ts) - \tau \cdot \max_{f,\sigma}(ts), \max_{f,\sigma}(ts)], \text{ where} \end{aligned}$$

- $f_{\sigma}(i)$ is the feature value of i^{th} maximal occurrence of σ ,
- $\min_{f,\sigma}(ts)$ (resp. $\max_{f,\sigma}(ts)$) is the minimum (resp. maximum) feature value among all maximal occurrences of σ within ts .

Definition 4 (extreme pattern occurrence). *Given a regular expression σ and a set of distinct features f_1, f_2, \dots, f_k , a maximal occurrence of σ in a time series ts is an extreme occurrence of σ wrt f_1, f_2, \dots, f_k iff all corresponding feature values are extreme feature values for σ in ts .*

3.2 Identifying quasi-periodic extreme patterns

Definition 5 (footprint). *Given a time series $ts = x_0, x_1, \dots, x_{n-1}$ and a pattern p , the footprint of p over ts is the sequence $fp = q_0, q_1, \dots, q_{n-1}$ of the same length as ts where each $q_k \in fp$ is an integer between 0 and n such that:*

- $q_k = 0$ if index k does not occur in any i -occurrence of the pattern p in the input time series ts .

- $q_k = j > 0$ if index k belongs to the j^{th} i -occurrence of the pattern p when reading the time series ts .

Definition 6 (footprint distance). The footprint distance between the j^{th} and the $(j+1)^{\text{th}}$ maximal occurrence of a pattern p in a time series ts is the number of zeros in the footprint of p over ts between the end of the j^{th} i -occurrence of p in ts and the start of the $(j+1)^{\text{th}}$ i -occurrence of p in ts .

Definition 7 (found distance). The found distance between the j^{th} and the $(j+1)^{\text{th}}$ occurrence of a pattern p in a time series ts is the difference between the two corresponding found indices.

Definition 8 (distance). Consider a pattern p for which the length of its smallest occurrence is $\ell > 0$. The distance between the j^{th} and the $(j+1)^{\text{th}}$ maximal occurrence of a pattern p in a time series ts is the footprint distance iff, given any occurrence o of the pattern p , all prefixes and suffixes of o for which the minimum length is greater than or equal to ℓ are also occurrences of the pattern p , and the found distance otherwise.

Definition 9 (quasi-periodic pattern of order g). Let g and δ be two natural numbers with $g > 0$, p a pattern, ts a time series and o_p the sequence of all maximal occurrences of p in ts . In addition let e_p be a subsequence of o_p of size at least $\ell = 3g$. Let d_p and \overline{d}_p be resp. the minimum and the maximum distance between any j^{th} and $(j+g)^{\text{th}}$ maximal occurrences of p in e_p , with $i \in [1, \ell - g]$. Then p is said to be a quasi-periodic pattern of order g and period $[d_p, \overline{d}_p]$ iff

1. $\overline{d}_p - d_p \leq \delta$,
2. the first maximal occurrence of $p \in e_p$ is located at a distance $d \leq \overline{d}_p$ from the beginning of ts ,
3. the last maximal occurrence of $p \in e_p$ is located at a distance $d' \leq \overline{d}_p$ from the end of ts .

When e_p corresponds to all maximal occurrences (resp. all extreme occurrences) of p then p is a periodic pattern (resp. periodic extreme pattern) of order g .

Example 1. We illustrate the previous definitions on the time series 0, 2, 9, 8, 10, 1, 0, 0, 3, 0, 8, 1, 9, 1, 1, 1, 2, 9, 9, 2, 2, 8, 0, 1, 0. For this purpose we consider the PEAK (resp. STEADY_SEQUENCE) pattern defined by ‘ < (= | <)* (> | =)* > ’ (resp. ‘ =+ ’) and by the trimming parameters $b = a = 1$ (resp. $b = a = 0$). The eight (resp. four) subsequences outlined in yellow between two vertical red bars on top (resp. at the bottom) of Figure 1 correspond to the eight s-occurrences of the PEAK (resp. STEADY_SEQUENCE) pattern.

The distance of the PEAK pattern is defined as the found distance since not all large enough suffixes of a maximal occurrence of peak correspond to a peak, i.e. the suffix ‘ >> ’ of the second maximal occurrence of peak ‘ <>> ’ is not a peak itself. Consequently the distances 2, 4, 2, 2, 6, 3, 2 between consecutive maximal occurrences of peaks are defined as the difference between their corresponding found positions, outlined with a vertical arrow in the upper part of Figure 1.

The distance of the STEADY_SEQUENCE pattern is defined at the footprint distance since all large enough prefixes and suffixes of ‘ =+ ’ also correspond to a steady sequence. Consequently the distances 6, 2, 1 between consecutive maximal occurrences of steady sequences are defined as the difference between the start of a maximal occurrence of the pattern and the end of the maximal occurrence of the previous pattern.

We now focus on the extreme occurrences of the PEAK pattern wrt the max feature assuming a threshold $\tau = 0.2$. Such feature values 9, 10, 3, 8, 9, 9, 8, 1 are shown in the lower part of Figure 1. Among them only the values 9, 10, 8, 9, 9, 8 belong to the interval $[10(1 - \tau), 10]$, and consequently only the first, second, fourth, fifth, sixth and seventh peak maximal occurrences are extreme. Now assume a period threshold $\delta = 2$. Since the minimum/maximum distance between any j and $j + 1$ positions of extreme pattern occurrences is equal to $2/6$, the correspond range $6 - 2$ is greater than $\delta = 2$. Consequently the corresponding sequence of extreme peaks is not quasi-periodic of order 1. But it is quasi-periodic of order 2 because (1) the minimum/maximum distance between any j and $j + 2$ positions is equal to $8/10$, and (2) the first (resp. last) occurrence of peak is not too far from the leftmost (resp. rightmost) border.

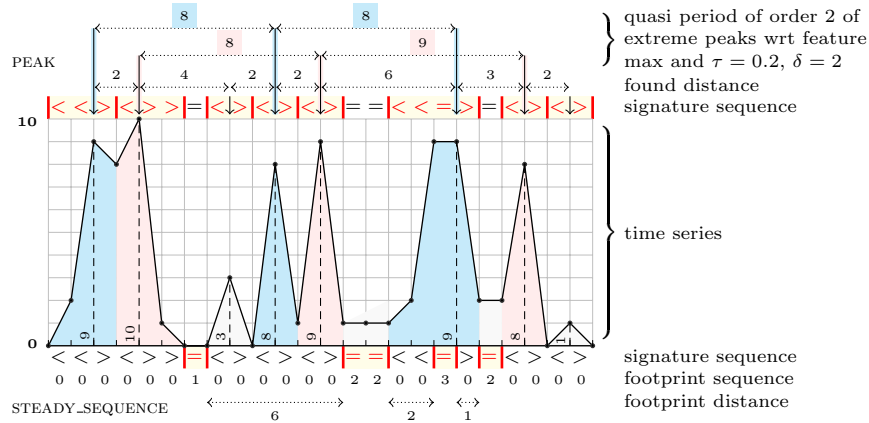


Fig. 1: Illustrating the notions of signature, found distance, footprint distance, extreme patterns and quasi-periodic extreme patterns wrt the PEAK=‘ < (= | <)*(> | =)* > ’ and STEADY_SEQUENCE=‘ =+ ’ patterns

3.3 CP-based time series annotation

In all what follows, a positive (respectively negative) workload trace or time series is a workload trace or time series that do not present any anomaly (respectively that is abnormal). The purpose is to label a set of historical traces as being

either positive or negative. As a first step, we begin with a small set of time series that are prelabelled as positives. From those sample time series, we identify a set $E_p = p_1, \dots, p_n$ of quasi-periodic extreme patterns and we compute their respective periods. This process is presented in Algorithm 1, where:

- procedure *compute_extreme_occurrences*(s_t, f, p, e_t) uses Definition 4 to computes the list of all extreme occurrences of the pattern p with respect to the feature f and the threshold e_t .
- procedure *compute_period*(EV, p_t, g) uses Definition 9 to check if the extreme occurrences in the list EV are quasi-periodic of order g . If yes computes and return the period, else it returns the empty set.

Algorithm 1 Algorithm to acquire a CP model out of positive time series

PROCEDURE *LearnCPModel*(S, P, F, e_t, p_t) : (*Model*)

```

1:  $S$ :          Positive time series set,
2:  $P$ :          Set of patterns to consider,
3:  $F$ :          Set of features to consider,
4:  $e_t \in [0, 1]$ : Extreme value threshold,
5:  $p_t \in \mathbb{N}$ :  Period threshold.
6:
7:  $st \leftarrow \{\}$ 
8:  $Model \leftarrow \{\}$ 
9: for all  $s \in S$  do
10:    $st \leftarrow st \oplus s$  ▷ Concatenate all positive time series into  $st$ 
11: end for
12:  $\bar{g} \leftarrow$  max order to consider
13:  $Periods \leftarrow \emptyset$ 
14: for all  $(f, p) \in F \times P$  do
15:   for all  $g \in [1, \bar{g}]$  do
16:      $EV \leftarrow compute\_extreme\_occurrences(s_t, f, p, e_t)$ 
17:      $Period_{f,p,g} \leftarrow compute\_period(EV, p_t, g)$ 
18:      $Periods \leftarrow Periods \cup Period_{f,p,g}$ 
19:   end for
20:    $Model \leftarrow Model \cup (f, p, Periods)$ 
21: end for
22: return  $Model$ 

```

Each of the remaining traces is labelled as positive if it presents all the quasi-periodic extreme patterns of P , with compatible periods (periods whose intersection is non-empty) i.e. if it satisfies the CP model acquired by Algorithm 1. The traces that do not satisfy the constraints of the model are labelled as negatives. This process is described in Algorithm 2. The next step trains a model that can detect anomalies at run time. The next section details the specificities of our model.

Algorithm 2 Using an acquired CP model to label time series

PROCEDURE *LabelTimeSeries*(st, M, e_t, pt) : ($ts, label$)

```
1:  $st$ :      Time series to label,
2:  $M$ :      Learned model,
3:  $e_t \in [0, 1]$ : Extreme value threshold,
4:  $p_t \in \mathbb{N}$ : Period threshold.
5:
6: for all  $[(f, p, Periods)] \in M \times P$  do
7:    $EV \leftarrow compute\_extreme\_occurrences(st, f, p, e_t)$ 
8:   for all  $Period_{f,p,g} \in Periods$  do
9:      $TSPeriod_{f,p,g} \leftarrow compute\_period(EV, p_t, g)$ 
10:    if  $\neg IsCompatible(TSPeriod_{f,p,g}, Period_{f,p,g})$  then
11:       $label \leftarrow negative$ 
12:      return ( $s_t, label$ )
13:    end if
14:  end for
15: end for
16:  $label \leftarrow positive$ 
17: return ( $s_t, label$ )
```

4 Anomalies detection

Given a workload trace, an anomaly is said to occur iff a quasi-periodic extreme pattern, identified by the CP model acquisition step, does not occur at an expected location. In Sections 4.1 and 4.2, we propose two distinct approaches to predict those anomalies. The first one relies on a constrain programming model as a pre-training step while the second one relies on k-means clustering.

4.1 Supervised learning method

Supervised learning [9] is a class of machine learning algorithms that aim at learning a function that computes an output from an input observation. In order to compute that function, supervised learning algorithms rely on input examples together with the expected output value.

In this section we show how we use a deep neural network to detect malfunctions in a cloud infrastructure.

Neural network model There is no state-of-the-art method to set the parameters of a neural network [16]. This section presents all the empiric choices relative to our model.

Deep neural network architecture

- Input layer. The choice here is intuitive. Our workload traces are made up of time series representing daily workloads with a time step of 10 minutes. It means that each workload trace is a time series of 144 values, we thus chose 144 as the number of neurons in the input layers.

- Hidden layers. We empirically chose 2 hidden layers of 10 neurons each.
- Output layer with two neurons.
Having two neurons in the output layer, the results are interpreted in the following way. The first neuron’s value is the probability that we predict the first category i.e. *abnormal*, and the second neuron’s value is the probability that we predict the second category *normal*.

Optimisation

- Activate function. We chose *softmax* as activation function since we need to output probabilistic values between two discriminative classes [16].
- Stochastic gradient descent. The output y of a neural network given an input X is given by Equation 1 where f is the activate function, W is the weight matrix and B is the bias matrix [16].

$$y = f(WX + B) \tag{1}$$

To set the parameters W and B during the learning, we used the standard stochastic gradient descent technique with randomly shuffling the training examples. As shown in [7], it performs better than sequential selection of examples that are grouped by classes as it is the case in our model.

4.2 Unsupervised learning method

Unsupervised leaning [12] is a machine learning technique that consists in inferring a discriminative function out of an unlabelled set of data.

One of the most popular and yet simple unsupervised learning algorithm is *k-means* [14]. *k-means* partitions a set of unlabelled data into k partitions according to a given metric. One difficulty in using *k-means* is to choose k the number of clusters, as there is no mathematical criterion [19].

In the context of our application, we did not encounter that difficulty, as we already know, that we want to discriminate between two categories, *normal* and *abnormal*. Therefore we set $k = 2$ and we use the Euclidean distance as the distance metric.

The steps required to use the k-means clustering algorithm to predict an anomaly in a time series ts are the following:

1. Learning step: The purpose is to partition the dataset into two clusters.
 - Select a known normal time series ts_n and a known abnormal one ts_a .
 - Set ts_a and ts_n to be the initial centroids for k-means clustering.
 - Cl_a and Cl_n are the two clusters obtained from the dataset, such that $ts_a \in Cl_a$ and $ts_n \in Cl_n$
2. Prediction step:
 - Computes the centroids c_a and c_n of Cl_a and Cl_n respectively.
 - ts is normal (positive) if $d(ts, cn) \leq d(ts, ca)$ and abnormal otherwise, where $d(x, y)$ is the Euclidean distance between the points x and y .

5 Experiments

In this section, we evaluate each step of our method to predict malfunction in a data centre, we also show the necessity of reinforcing the learned constraint programming model with the neural network of Section 4.1. We further evaluate the unsupervised based learning of Section 4.2.

5.1 Dataset

The initial input to our framework is a set of historical workload traces provided by a French SME company specialised in virtualised data centre analysis. Figure 2 shows an instance of raw historical workload traces. Each curve of the figure represents the CPU workload of a VM in a data centre for a whole day in the interval 23rd of February 2017 to 26th of October 2017.

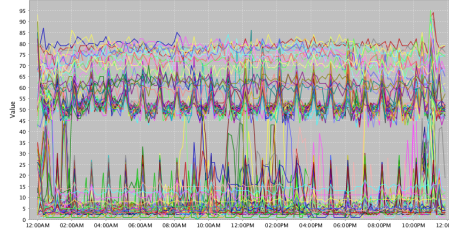


Fig. 2: Unlabeled historical data

5.2 Implementation of the CP based labelling

We implemented Algorithm 2 of Section 3.3 with SICStus Prolog [8].

Figures 3 and 4 shows how the initial unlabelled dataset of Figure 2 is partitioned into two distinct subsets using Algorithm 2 of Section 3.3.

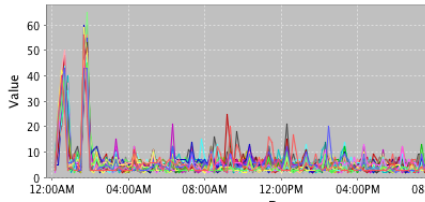


Fig. 3: Workloads automatically labelled as normal by the CP model

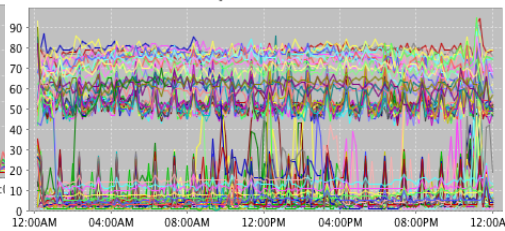


Fig. 4: Workloads automatically labelled as abnormal by the CP model

From Figure 3 we can observe that the quasi-periodic pattern acquired by the CP model is the occurrence of two extreme peaks every day between midnight and 3AM. However, as we will see in Section 5.3, we should take care of some false negative annotations.

5.3 Neural network reinforcement of the CP model

The constraint programming model learned using Algorithm 1 can be used with Algorithm 2 to label workload traces, i.e. it can also be used to detect malfunctions in a given workload. However, the quality of the CP model strongly rely on the threshold $\tau \in [0, 1]$ of Definition 3. This threshold sets the magnitude above and below which a feature value is considered extreme.

Figure 5 shows that the choice of value of $\tau \in [0, 1]$ is a trade-off between the percentage of false positive and false negative predicted by the model.

Figure 5 induces the following observations:

- For a threshold value above 0.4, i.e. for $\tau \in [0.4, 1]$ the percentage of false positive predictions of the models grows exponentially. This is not suitable as a false positive prediction is when the model fails to predict a malfunction.
- On the other $\tau \in [0, 0.4]$, the percentage of false negative prediction is close to 100. This is also not suitable as it means that the model predicts a malfunction in almost every workload.

The best trade-off threshold value is thus 0.4. Although $\tau = 0.4$ implies a perfect 0% false positive predictions, it also implies around 12% false negative predictions. This is the reason why we use a neural network on top of the CP model. The CP model provides a good learning base for the neural network.

5.4 Neural network versus K-means prediction

The purpose of the neural network in our framework is to capture hidden structures within the dataset. We implemented the model presented at Section 4.1 in Python using Tensorflow [1]. The amount of false positive and false negative predictions using the so trained neural network are both 0%.

Figure 6 shows how the precision of the model gets high over the learning steps. The precision is evaluated with the cross entropy loss function. We can see that the loss rapidly converges to value 0.

On the other hand, the prediction using the k-means method suffers from the fact that it is based on a notion of closeness through Euclidean distance. The dataset depicted at Figure 2 is therefore separated in two partitions. The direct consequence is the amount of false positive prediction that is above 70%. While a model with a reasonable false negative prediction rate may remain exploitable, the inverse is not desirable. A false negative prediction in our context means that the model fails to predict a malfunction. A 70% false positive rate makes the k-means model not exploitable in this context.

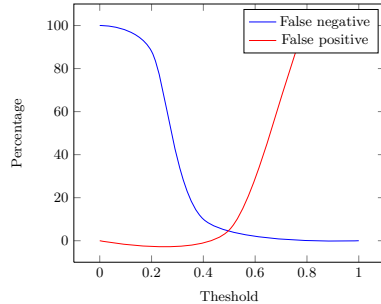


Fig. 5: False positive against false negative trade-off of the CP model

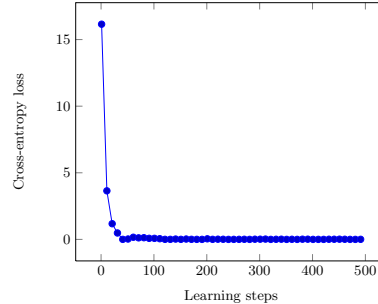


Fig. 6: Learning graph of the neural network model

6 Conclusion

In this paper we first introduced the generic notions of *extreme patterns* and *quasi-periodic pattern group* to capture the behaviour of a time series. Using those notions, we described a machine learning framework for anomaly detection in a cloud workload trace. To overcome the problem of deep unsupervised learning, we proposed a method that relies on constraint programming through the definition of quasi-periodic extreme pattern to annotate the workload time series. After acquiring a constraint programming model, the data set is automatically annotated and fed to a neural network for prediction. Experimental results on real workload traces show that state of the art unsupervised learning methods like K-means are not exploitable in our context, and that the combination of a constraint programming model and a neural network produces better results.

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