Ensemble-based prediction of business processes bottlenecks with recurrent concept drifts

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Ensemble-Based Prediction of Business Processes Bottlenecks With Recurrent Concept Drifts

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ABSTRACT
Bottleneck prediction is an important sub-task of process mining that aims at optimizing the discovered process models by avoiding such congestions. This paper discusses an ongoing work on incorporating recurrent concept drift in bottleneck prediction when applied to a real-world scenario. In the field of process mining, we develop a method of predicting whether and which bottlenecks will likely appear based on data known before a case starts. We next introduce GRAEC, a carefully-designed weighting mechanism to deal with concept drifts. The weighting decays over time and is extendable to adapt to seasonality in data. The methods are then applied to a simulation, and an invoicing process in the field of installation services in real-world settings. The results show an improvement to prediction accuracy compared to retraining a model on the most recent data.

KEYWORDS
Complex event processing, data streams, recurrent concepts, data mining, knowledge discovery, adaptation methods, process mining

1 INTRODUCTION
Concept drift expresses an occurrence of a shift in relations between input and output data over time. The challenge with concept drift is that it is difficult to assess, detect, and correct such evolutions. One method of solving concept drift is to retrain models periodically. This method poses two major disadvantages. First, this reduces the quantity of available data, which is a big issue when the number of data points per time unit is low, or when dealing with unbalanced datasets. The combination of these two causes over-fitting of the model on larger classes. Second, retraining a model with new data inherently discards former data, which could remove valuable information on seasonality.

This paper discusses a technique to cover both issues and applies it to reduce the duration of a process, by predicting if, and where, bottlenecks take place in the process. A simple example for a paper submission process is shown in Figure 1, where the bottlenecks are indicated for process instances at different points in time. Note the bottle activities for papers on Process Mining. The proposed solution uses multiple machine learning models trained over different intervals of previous data, and assigns weights to the predictions of each model based on the difference in time between the model and the test data, factoring in an exponential decay (giving priority to recent models) and a periodic function (giving priority to seasonally similar points in time). As such we develop a Gradual and Recurrent concept drift Adapting Ensemble Classifier, or GRAEC. The contributions of this paper are:

- A mathematical way for assessing bottlenecks in business processes
- A novel concept drift adaptation method, GRAEC
- An extensive experimental evaluation using a simulation study and a real-world dataset, which proves the superiority of our method compared to existing solutions which also proves the correctness of our concept

The rest of the paper is organised as follows. Section 2 discusses some related literature. Section 3 defines the problem that this paper aims to solve. Section 4 proposes a solution to adapting for concept drift with seasonality. Section 5 describes the experimental set-up for the simulation and the real-world dataset. Section 6 presents and discusses the results of the experiment. Section 7 concludes the paper and provides suggestions for future research.

2 RELATED WORK
Concept drift has been a topic in online data streams in recent years. Concept drift is the phenomenon where relations between input (features) and output (labels in the case of the experiments in this paper) change over time, because the underlying models and/or distributions change [5]. Much of existing literature is on detecting concept drift. Techniques for detection include sudden changes in classification accuracy (such as in [1]), or changes in feature importance (such as in [17] and [3]). Detecting concept drift is a first step, adapting to it is the next. One way to do so is by simply retraining the model whenever a drift in concept is detected. A disadvantage of this technique occurs if the drift is periodic, i.e., a drift of concept is detected, but the previous concept may still be of use at a later point in time, just not right after the detected drift. [20] trains a model for every given number of data points, and then creates an ensemble classifier, weighting each model according to the accuracy assessed on the most recent data points.

The challenges of seasonal concepts, or what is more known in the literature as recurrent concepts, have been addressed recently in [4, 9, 13, 15, 16]. The general idea of approaches handling recurring concepts is not to lose knowledge gathered over time. Therefore, they maintain a pool of classifiers and use one or an ensemble of them each time. Our approach is bringing the benefits of ensemble-based recurrent concept drifts to the domain of business process intelligence for predicting bottlenecks.
The problem discussed in this paper is to adapt to concept drift in business processes, and improve these predictions by accounting for concept drift. The authors use information about the process execution (Control-flow perspective) as well as involved data (Data-perspective). They show the effectiveness of incremental machine learning algorithms such as Adaptive Hoeffding Option Trees [2] in handling different types of concept drift, amongst which recurrent concept drift. Different to this approach, our novel method introduced in this paper implements an ensemble classifier to adapt to recurrent concepts.

3 PROBLEM DESCRIPTION

The problem discussed in this paper is to adapt to concept drift when applied in the domain of business processes analysis. The focus of the paper is on the effectiveness of the proposed concept drift adaption method, finding the bottlenecks is the use case.

We aim to improve the throughput of the process by indicating bottleneck activities based on information we have before the case starts. In our toy example of paper submissions, such information could be the author(s), the research area, the number of publications each author has, and the number of pages in the paper, all of which are known once a submission is made. Using this information we then predict which of the activity will be the bottleneck activity. This bottleneck is then considered as a label for classifiers, which are trained using the information of the case as input.

We assume that the process is stable, i.e. our research is limited to processes whose structure does not change over time. The time evolution we are looking at is that of the relations between case information and bottleneck labels, i.e. the drift in the underlying statistical models.

4 PROPOSED SOLUTION

The problem this paper addresses is predicting bottleneck activities in business processes, and improve these predictions by accounting for concept drifts. The goal is not to indicate or explicitly detect concept drift, but to optimise the use of selected previously trained models to improve prediction quality. This section describes the proposed solution, first introducing the context of business processes (Subsection 4.1), next assessing what activity is a bottleneck activity (Subsection 4.2), and finally improving predictions using GRAEC (Subsection 4.3). We discuss them in general and also in applying them to a simulation and a case study in Section 5.

4.1 Business Processes

Process mining is field of research that bridges the gap between the computational possibilities of data mining with the industrial application of business processes, by learning process behaviour from event logs. Event logs consist of events, each describing what happened (Activity), at what time (Time), by whom (Resource), for which process instance (Case ID). They show the effectiveness of incremental machine learning algorithms such as Adaptive Hoeffding Option Trees [2] in handling different types of concept drift, amongst which recurrent concept drift. Different to this approach, our novel method introduced in this paper implements an ensemble classifier to adapt to recurrent concepts.
presented in Section 5. In other processes some notion of the start of the process (like an automated trigger caused by a client) needs to be identified to analyse the throughput of the first activity.

In the example of Figure 1, each case is one submission. The Case ID could be a DOI, the activity set A would be \{Submit, Assign reviewers, Review1, Review2, Review3, Combine reviews, Send notification\}. Events would relate these two together, providing information on when an activity for the given paper was completed. The process consists of only one variant, i.e. there is only one way to follow the process.

### 4.2 Bottleneck Assessment

Let \( C \) be a set of cases. We want to find bottlenecks in cases that have a long duration. We partition the set of cases into \( H_1 \) and \( L_i \), each representing cases that take up to a given time \( d \) (High-throughput) and cases that take more than \( d \) (Low-throughput) respectively, for variant \( i \) for \( i \in 1...N \), \( N \) being the total number of variants in \( C \). For activities to be considered bottlenecks, we have two requirements: Relevance and Resolvability.

If an activity has a long duration compared to other activities, but a short duration compared to other activities in the same case, it will be less effective to resolve a long duration of that activity than activities that take up a larger part of the case duration. We formalise this Relevance requirement by requiring that the fraction of the total case duration of the activity is at least \( \alpha \), where \( \alpha \in [0, 1] \) is a parameter chosen on domain expert’s recommendation and process characteristics (like the number of activities). Note that setting \( \alpha \) to 0 drops the relevance requirement entirely. Further note that if \( \alpha \) is set too high, no activities will meet this requirement. It will hence be important to find an appropriate balance or to have a fall-through mechanism to label cases.

An activity is resolvable if it has a longer duration than a benchmark average for that activity. We only address bottlenecks in \( L_i \), as such we use the average duration of the activity in \( H_i \) as benchmark. This is the Resolvability requirement. We know that there must be at least one activity that satisfies this requirement, since the sum of all durations (i.e. the duration of the case) of any case in \( L_i \) is larger than the duration of any case in \( H_i \), so at least one activity must take longer than the average of that activity in \( H_i \).

Finally, of all activities that pass both requirements, we choose the activity that deviates the most (in terms of the standard deviation in \( H_1 \) from the benchmark average). This way ensures that the chosen bottleneck is least explained by the intrinsic variability of real-world processes. This procedure is described in Algorithm 1.

Line 1 loops over each Variant of \( C \). First we derive the Trace of the Variant in Line 2. Note that this is the same as \( \text{act}(L_i) \). In Lines 3 and 4 we label each case in \( H_1 \) as short. Lines 7 and 8 calculate the sample mean and standard deviation\(^1\). We next consider each case with a long duration in Lines 10 - 19. First we take all indices of the Trace in Line 11. Next we apply the Resolvability requirement in Line 12, and the Relevance requirement in Line 13. We then check if there is any activity that meets both requirements in Line 14. If there is, we apply as the label the activity whose duration deviates the most standard deviations from the mean throughput (assessed in Lines 8 and 7 respectively) in Line 15. If there are no activities that satisfies both requirements, we take the activity with the longest duration that satisfies the Resolvability requirement, in Line 17.

#### Algorithm 1: Selection of the bottleneck

**Result:** Each case \( c \) in \( C \) gets a label \( \text{label}(c) \)

1. for \( i = 1 \ldots N \) do
2. \( \sigma \leftarrow \text{act}(H_i) \)
3. for \( c \in H_i \) do
4. \( \text{label}(c) \leftarrow \text{short} \)
5. end
6. for \( k \in 1 \ldots |\sigma| - 1 \) do
7. \( x_k \leftarrow \frac{1}{|H_1|} \sum_{c \in H_1} c(k).\text{time} - c(k-1).\text{time} \)
8. \( s_k \leftarrow \sqrt{\frac{\sum_{c \in H_1} (c(k).\text{time} - c(k-1).\text{time} - x_k)^2}{|H_1|}} \)
9. end
10. for \( C \in L_i \) do
11. \( K_0 \leftarrow 1 \ldots |\sigma| - 1 \)
12. \( K_1 \leftarrow \{ k | k \in K_0 : c(k).\text{time} - c(k-1).\text{time} > s_k \} \)
13. \( K_2 \leftarrow \{ k | k \in K_1 : \frac{c(k).\text{time} - c(k-1).\text{time}}{\text{duration}(c)} \geq \alpha \} \)
14. if \( |K_2| \neq 0 \) then
15. \( \text{label}(c) \leftarrow c(\text{arg max}_{k \in K_2} \left( \frac{c(k).\text{time} - c(k-1).\text{time}}{s_k} \right) ).\text{act} \)
16. else
17. \( \text{label}(c) \leftarrow c(\text{arg max}_{k \in K_1} c(k).\text{time} - c(k-1).\text{time}).\text{act} \)
18. end
19. end
20. end

\(^1\)We could also have taken the population standard deviation, it does not make a difference since the sample size is the same for each activity.

### 4.3 Incorporating the Effect of Concept Drift

This subsection proposes a method of dealing with concept drift. The general idea is to split available training data into smaller sets, and give weights to the models created by each set. The method is general, and we will demonstrate its effectiveness in our use case of predicting bottlenecks.

Let \( D \) be our dataset, and the points in \( D \) be \( d_i \). Each datapoint has input features \( d_i.x \), a timestamp \( d_i.t \), and a label \( d_i.y \). In our use case of business process bottleneck prediction, \( d_i \) is a case, \( d_i.x \) is information about a case, \( d_i.t \) is the timestamp of the first event of a case, and \( d_i.y \) is the bottleneck as labelled by Algorithm 1.

In the light of Figure 1, \( d_i.x \) would be information on the author(s), the research area, the number of publications each author has, and the number of pages in the paper. \( d_i.t \) would be the time of the submission, and \( d_i.y \) would be the bottleneck, as indicated in Figure 1.

\( D \) contains data over a time period of length \( T = \max_{d_i \in D} d_i.t - \min_{d_i \in D} d_i.t \). This length is divided into smaller data sets \( D_j \), each with length \( S \), such that \( d_i \in D_j \rightleftharpoons \lfloor \frac{d_i.t}{S} \rfloor = j \). In this paper \( S \) is regarded as a constant in time, and different values of
Algorithm 2: Determination of weights

<table>
<thead>
<tr>
<th>Result: For the test prediction $d$, each model $M_k$ gets a weight $w_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$j \leftarrow \lfloor \frac{d.time}{S} \rfloor$</td>
</tr>
<tr>
<td>for $k = 0 \ldots j - 1$ do</td>
</tr>
<tr>
<td>$w_k \leftarrow 10^{-(j-k+1)\beta}$</td>
</tr>
<tr>
<td>end</td>
</tr>
<tr>
<td>$t \leftarrow d.time - p$</td>
</tr>
<tr>
<td>while $t &gt; 0$ do</td>
</tr>
<tr>
<td>$k \leftarrow \lfloor \frac{t}{p} \rfloor$</td>
</tr>
<tr>
<td>$w_k \leftarrow w_k + \tau$</td>
</tr>
<tr>
<td>$t \leftarrow t - p$</td>
</tr>
<tr>
<td>end</td>
</tr>
</tbody>
</table>

$p_i = \sum_{0 \leq k \leq j-1} w_k \cdot p_{i,k}$

where $w_k$ is the weight of the described above. The predicted label is then arg max $\beta$. The combination of $\beta$, $\tau$ and $p$ uniquely identifies a weighting assignment, together with $S$ we form a complete concept drift adaption technique. Since this technique adapts to gradual and recurrent drift, we will refer to it as Gradual and Recurrent concept drift Adapting Ensemble Classifier, or GRAEC. Finding the best combination of $\beta$, $\tau$, $p$ and $S$ is part of the training process. In this paper we will restrict to a single value for $p$.

5 SIMULATION AND CASE STUDY SETUP

This section describes the simulated (Subsection 5.1) and real-world data set used (Subsection 5.2), the experimental setup (Subsection 5.3), and additional information about how the models are trained (Subsection 5.4). The goal of the case study is to test the effectiveness of our proposed method. The actual predicted bottlenecks is of interest to the company, but falls outside the scope of this paper.

The code to run the full Simulation experiment including the implementations of Algorithms 1 and 2 is available at https://github.com/yorick-spenrath/GRAEC.

5.1 Simulation Setup

We simulate an event log based on the running example. We use three features: the topic, the number of pages used in the paper, and the number of publications the author has. The topic is used to determine where a bottleneck will be, and the number of pages is used to determine if there will be a bottleneck. As such, the number of publications will not influence the simulation. The topic is one of the following: 'Machine Learning' (ML), 'Data Mining' (DM), 'Process Mining' (PM), and 'Operations Management' (OM). The number of pages and the number of publications are both integers in the interval $[1,100]$, drawn at random. We simulate for 5 years of data, where we receive 200 papers of each topic each month (for a total of 800 cases per month, or 48000 over the simulation). Time is measured in months, and months consist of 30 days each, i.e. the start of all cases in the first month have a time between 0 and 1, and a day takes $\frac{1}{30}$ units of simulation time. The start of the case coincides with the timestamp of the submit event.
We analyze part of the repair process at a Dutch installation services company. Their repair process is roughly divided into three steps: preparation, repair, and invoicing. We have an event log of about 80,000 events, with information on the resource and the time stamp of each activity, the timestamp the other events is the timestamp of the preceding event, increased by a random variable $X$, which is in the light of Subsection 4.1, is considered as the full process of the bottleneck to the case, if the number of pages is outside the interval $[\beta \cdot \alpha + \theta, \beta \cdot \alpha + 20]$. This is visualised in Figure 3.

We add gradual concept drift by selecting an interval of size $\Delta = \{0, 7, 14, 21, 28\}$, one for each value of $S$. Each of the $\Delta$ contains data about cases that started in $[S \cdot j, S \cdot (j+1)]$. Note that cases could have different bottleneck labels for different values of $S$, as a result of being compared within a different set in Algorithm 1. $d$ and $\alpha$ are set to 21 days and 0.2 respectively. For the simulation dataset, this is set by the simulation design, for the real-world dataset this is the recommended value for the company’s domain expert. After labelling each set, the number of datapoints in each subset is reduced using $k$-medoids with Jaccard distance, to ensure that the largest class in a subset is at least twice as big as the smallest class, to reduce overfitting. This is not required for the real-world dataset as it is already balanced by design. For each subset $D^S_j$, a model $M^S_j$ is trained using the method described in the next subsection.

We then compare three different approaches. The first approach uses only the first year of data to create a single model, which is then used for all testing. This will be referred to as the Naive method. The second approach uses the model created from the dataset, which was most recently completed; if a datapoint of $D^S_j$ is tested, model $M^S_{j+1}$ is used. This approach will be referred to as the Recent method. Finally, we use our approach, which will be referred to as GfEC. Each method is tested on each value of $S$. Note that this also creates four configurations for the Naive method, since a different $S$ results may result in different labelling.

We next use the full last year of data for evaluation. This part is split in a stratified 80% - 20% train-test split. The train split is used to assess all approaches. Unless otherwise stated, the explanation holds for the simulation study as well as the real-world dataset.

From $L$ we create four different datasets $D^S$, one for each value of $S$. Each $S \cdot L$ is split into smaller subsets $L^S_j$, each of duration $S$, as discussed in Section 4.3. This creates subsets $D^S_j$, where information about cases (topic, pages, and publications for the simulation, client information for the Real-world dataset) are related to labels, for period $j$. $D^S_j$ contains data about cases that started in $[S \cdot j, S \cdot (j+1)]$. Note that cases could have different bottleneck labels for different values of $S$, as a result of being compared within a different set in Algorithm 1. $d$ and $\alpha$ are set to 21 days and 0.2 respectively. For the simulation dataset, this is set by the simulation design, for the real-world dataset this is the recommended value for the company’s domain expert. After labelling each set, the number of datapoints in each subset is reduced using $k$-medoids with Jaccard distance, to ensure that the largest class in a subset is at least twice as big as the smallest class, to reduce overfitting. This is not required for the simulation dataset, as it is already balanced by design. For each subset $D^S_j$, a model $M^S_j$ is trained using the method described in the next subsection.

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of a dataset, all using the implementation of the scikit learn library in Python [14]. The remaining 20% is then used to pick the best model out of the four optimised algorithms. Because of this, we require that \( D^S_j \) has at least 10 entries in each of its labels and that it has at least 2 different classes. For the real-world dataset, some \( D^S_j \)’s might fail to meet one or both of these requirements. This means that those \( D^S_j \)’s will not be used for training, and as such the respective model \( M^S_j \) may not exist. GRAEC is not limited by this, but having too few \( M^S_j \)’s will have a negative impact on the effectiveness of GRAEC. If we cannot make a prediction for a datapoint in \( D^S_j \) because of a missing model \( M^S_{j-1} \), we will use the most recent model instead (\( M^S_{j-2} \) or even earlier models).

6 RESULTS AND DISCUSSION

In this section we show the results of applying our approach to the simulation dataset and the real-world dataset described in the previous section. Since the proposed solution aims to adapt to overcome the effects of concept drift and not to detect it, we are only interested in the score, but not in the drift in the process or derived models themselves. In Subsection 6.1 we present and discuss the results of the simulation dataset, in Subsection 6.2 we do the same for the real-world dataset.

6.1 Simulation Study

The results of the simulation study are presented in Figure 4 and Table 2. Figure 4 shows the scores of each of the twelve methods applied. The best scores for GRAEC are underlined in Table 2 to indicate the optimal values of \( \beta \) and \( \tau \). Table 2 further shows the \( F_1 \) and accuracy scores for all configurations of \( \beta \), \( \tau \) and \( S \).

![Figure 4](image-url)  
Figure 4: The results of the Simulation in terms of \( F_1 \) scores. \( GR \) indicates the GRAEC method, \( R \) uses the most Recent model, and \( N \) creates a model once on the first year of the dataset. Each method is tested for different values of \( S \), indicated by the numbers. The values of \( \beta \) and \( \tau \) for GRAEC are underlined in Table 2.

6.1.1 The effectiveness of GRAEC. The foremost result is the effectiveness of GRAEC. When comparing the scores for each method for a given value of \( S \), GRAEC outperforms the other two methods. The best GRAEC score, for \( S = 1 \) outperforms every other option. This is expected, the design of the simulation was to make optimal use of the adaptions GRAEC could give for \( S = 1 \). The optimal parameters for GRAEC indicate the adaption for both gradual and recurrent concept drift.

6.1.2 The ineffectiveness of Naive. The Naive method is completely ineffective for any value of \( S \). This makes sense, since one year of data contains four different recurrent concepts. As a result the Naive model will not even be able to properly explain the dataset it was trained on, let alone datasets that only contain a single recurrent concept, and datasets on which the gradual drift has had more effect.

6.1.3 The effect of \( S \). We shortly discuss the effect of each value of \( S \) below. We will refer to the way topic the related to the bottleneck activity as a concept, and refer to this concept in quartile 1 as ‘A’, in quartile 2 as ‘B’, 3 as ‘C’, and 4 as ‘D’. A \( D^S_j \) can contain one or more concepts. For example, \( D^1_0 \) contains only concept ‘A’, as do \( D^1_1 \) and \( D^1_2 \), where as \( D^1_3 \) has concept ‘B’. On the other hand \( D^2_1 \) has concepts ‘A’ and ‘B’ in an equal number of cases. We hence refer to the concept of \( D^2_1 \) as ‘AB’, and in line, the concept of \( D^3_1 \) is ‘AA’, the concept of \( D^3_2 \) is ‘CCC’, and \( D^3_1 \) has concept ‘BBCC’.  

<table>
<thead>
<tr>
<th>( S )</th>
<th>( \beta = 0 )</th>
<th>( \beta = 1 )</th>
<th>( \beta = 2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>( F_1 )</td>
<td>ACC</td>
<td>( F_1 )</td>
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Table 2: Scores for simulation study. The underlined scores belong to the best accuracy scores for each \( S \), as presented in Figure 4.
from a different recurrent concept, decreasing the overall score of the Recent method.

$S = 2$ and $S = 4$ For $S = 2$ we will have 6 $D_j^3$’s per year, with concepts ‘AA’, ‘AB’, ‘BB’, ‘CC’, ‘CD’, ‘DD’. As a result it will be difficult to train models on the second and fifth $D_j^3$ each year (with concepts ‘AB’ and ‘CD’ respectively). For the Recent method, predictions are suboptimal because:

- in the third and sixth period each year predictions will be made with a bad model
- in the second and fifth period each year, only half of the cases are the same as the previous concept
- in the first and fourth period each year, none of the cases are the same as the previous concept

As a result, the Recent method has a lower score than for $S = 1$. GRAEC only has the disadvantage of the poor models during predictions in the third and sixth periods, because of the optimal value for $\tau$. The first, second, fourth, and fifth period belong to a single concept (‘A’ through ‘D’ respectively), and models of previous years are re-used. As a result, the negative effect on the score for GRAEC is weaker. The score is still weaker than for $S = 1$, since there is less adaption to gradual drift, due to the optimal value of $\tau$. For $S=4$, the arguments follow the same reasoning, though their effect is more present (resulting in a lower score). This is because all consecutive periods have different recurrent concepts.

$S = 3$ The effect of the recurrent concept drift, and how Recent fails to adapt to it while GRAEC does, is most evident for $S = 3$. Each $D_j^3$ will be off a completely different concept compared to $D_j^{3-1}$. This has a devastating effect on the Recent method, which can at best tell something about short cases. The GRAEC on the other hand scores almost as well as for $S = 1$. The slightly decreased score comes from the inability to capture the gradual concept drift. The optimal $\beta = 1$, combined with $\tau = 100$ causes the influence of models trained in different periods to be insignificant, and GRAEC only adapting to the recurrent concept drift.

6.2 Real-World Dataset

The results of the real-world study are presented in Figure 5 and Table 3. Figure 5 shows the overall scores of each of the twelve methods applied, and Table 3 presents the values of $\beta$ and $\tau$ that belong to each value of $S$ for GRAEC.

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<th>$\tau$</th>
<th>ACC</th>
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<th>$\beta$</th>
<th>$\tau$</th>
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<td>0.417</td>
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<td>0.267</td>
<td>0.259</td>
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</table>

Table 3: Optimal values for $S$, $\beta$, and $\tau$, and the Accuracy and $F_1$ scores for the real-world dataset.

The key result to take away from Figure 5 is that the improvement of GRAEC over Recent is present, albeit small. The most likely explanation is that there is no strong effect of recurrent concept drift present in the real-world dataset. This also matches the results for $\tau$; only $S = 28$ has a value for $\tau$ that puts significant weight to periodically similar models, though for $S = 28$, there will be two such models at best. Please note that the method: Recent does not exist, and that we used it as an intuitive method for comparison. The results do not disprove the effectiveness of GRAEC. The goal of GRAEC was to allow adaption to both gradual and recurrent concept drift. As is evident from the results for $\tau$, GRAEC is in essence self-correcting the lack of recurrent concept drift.

7 CONCLUSION AND FUTURE WORK

The results from the Simulation study show the potential of GRAEC. We have developed a method that can adapt to both gradual as well as recurrent concept drift. The case study on the real-world dataset shows improvement, albeit small, over retraining the data periodically. The Simulation study stresses the importance of a correctly chosen $S$.

Like the simulation study, the real-world scenario was analysed in a post-mortem setting; there was data on completed cases available during analysis. A future research direction is to apply the simulation study as an online setting and include online optimisation of $\beta$, $\tau$ and possibly $S$, to see if the adaptions to gradual and recurrent concept drift are still optimal. In such an online setting, care should be taken that supervised information is available with a delay; cases that start in a certain period might complete (long) after the period ends. In such a scenario, the most recent model available may not be from the preceding period. This is because all cases that started in the preceding period might not have ended once the next period starts. As a result both the Recent and GRAEC method will deteriorate, though we expect the Recent method to be more affected by this.

The advantage of the use of a weighted ensemble, as GRAEC, is the availability of different machine learning models. Since we build one model on each period, we can freely choose the type of model each time. A different method, such as described in [12] is to use incremental learners, i.e. we do not create new models from scratch, but keep updating an existing model. As they show, especially the Adaptive Hoeffding Option Tree from [2] adapts well
to recurring concept drift. The next step in this study is to compare the effectiveness of our proposed concept drift adaption to theirs, on their artificial data, our simulation study and our real-world data.

The weighting functions are based on related work and expert knowledge. In this work we have limited ourselves to one value for $p$. In future work, different values or a superposition of values could be created. Another update to GRAEC would be not to add weight to the single model from the period at $d$, but also additional weight to the period before and after $d$.

One interesting future further direction is to borrow concepts from the online process discovery of process models [8] in order to extract process models on the fly and apply advanced stream mining techniques over those [7, 6] to extract the best classifiers for each period of time in an efficient manner.

Additionally, we would like to address the relatively different problem of drift detection in the more complicated and realistic scenario where interval-based events are considered [11]. In the case of overlapping of such events, more relations are considered between these temporal events appear. Also, we would like to investigate the implementation of available online drift detection techniques for observing deviations in streaming conformance checking applications [19] and anytime stream classification [10].

REFERENCES


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