*Proceedings of the 21st International Conference on Modelling and Applied Simulation (MAS), 002*
19th International Multidisciplinary Modeling & Simulation Multiconference

2724-0037 © 2022 The Authors.
doi: 10.46354/i3m.2022.mas.002

# Applying Conformance Checking on Virtual Laboratory Experiments

Athanasios Sypsas[1,*] and Dimitris Kalles[1]

[1]Hellenic Open University, Parodos Aristotelous 18, Patras, 263 35, Greece

[*]Corresponding author. Email address: sipsas@gmail.com

## Abstract

Conformance checking, as part of an Educational Process Mining (EPM) framework, is gaining popularity as it enables evaluating learners' behavior within a learning process. During conformance checking, the recorded logs of a process are analysed with respect to whether they match the underlying process model. In this paper, we investigate the applicability of conformance checking in determining the potential use of a particular virtual laboratory activity in an educational setting, which is different to the one that this activity was originally designed for. Our approach aims to use EPM to offer educators the ability to estimate if a specific virtual laboratory is suitable for a new educational setting with relatively limited work from his/her side. To do so, we use Unified Modeling Language (UML) Activity Diagrams (ADs) to map the problem of conformance checking to a Petri net (PN) formalism. Then, we calculate the similarity of process models representing experiments using the simulation traces of the corresponding Petri nets and the log file produced by the experiment's simulated execution in a virtual laboratory. The feasibility of our approach is demonstrated on a virtual microscoping experiment.

**Keywords:** Educational Process Mining; Virtual laboratory experiments; Conformance checking

## 1. Introduction

Information and communication systems are widely used to support the educational procedure. Useful data is stored through extensive logging providing insightful information about learners' interactions with their peers and the learning material and the processes they went through (Bogarín, Cerezo, & Romero, 2018; Cairns, Gueni, Hafdi, Joubert, & Khelifa, 2015). However, to achieve impact of some significance, all collected data must eventually be completely understood and transformed to actionable and valuable information, (Athanasios Sypsas & Kalles, 2022; Tsoni, Stavropoulos, & Verykios, 2019). Apart from data, all logged educational processes can also serve as information resources, giving rise to a new research area, Process Mining (PM), which aims to monitor, discover and possibly improve processes by extracting knowledge from stored event logs (Trčka, Pechenizkiy, & van der Aalst, 2010). Though PM started from the business community, it migrated to the education field (Ghazal, Ibrahim, & Salama, 2017), under the term Educational Process Mining (Trčka et al., 2010).

In various educational institutions, including universities and secondary education schools, virtual laboratories are used to implement the appropriate experimental environment for learners. However, a simulator for a specific experimental procedure and specific instruments cannot, in principle, be used without changes in a similar experimental environment. Therefore, a possible adjustment of the experimental process is necessary in order to still achieve the educational goals of the experiment even if the experimental environment may alter among different educational settings (Sypsas and Kalles, 2021).

In an educational context, a process is defined as the sequence of necessary actions leading to a specific learning outcome. Various educational processes can be modeled and simulated (Atanasijević-Kunc & Karer, 2021). Specifically, in virtual laboratories, process models can be used to abstractly describe all equipment available in a real, physical, environment and the experimental processes carried out therein via simulation. EPM application on these processes, contributes to the deeper comprehension of experiments and learning flows, since the logged learners' actions are associated with the process models describing the standardized experimental procedures (Sypsas and Kalles, 2022).

The three main types of EPM are:

1. Process model discovery: The process model is built from event logs.
2. Conformance checking: The model is compared to the event log and deviations are detected.
3. Process model extension: The process model is extended or improved using information from the event logs.

Figure 1 below depicts how EPM is applied.

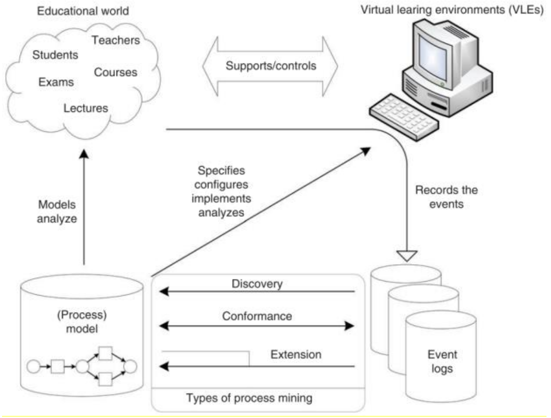


**Figure 1.** PM in education field (Bogarín et al., 2018)

When a process model is deployed, there may be a gap between the design and its implementation. For example the model processes are not exactly being executed in the way they were envisaged for (Estañol, Munoz-Gama, Carmona, & Teniente, 2018). This might be due to design or implementation faults, or because the model users do not follow the exact process actions. These situations can be recognized when conformance checking is used. This PM technique compares model processes with logged events and identifies deviations between model and reality (Van Der Aalst, 2012). Conformance checking techniques may also be used to measure how accurate a process model is (Fani Sani, van Zelst and van der Aalst, 2020). The standard conformance checking technique is alignments computation (van Zelst, Bolt, Hassani, van Dongen and van der Aalst, 2017). Depending on the application, the information that is carried out by alignments is not required. Only the alignment value has to be calculated to compare process models (Fani Sani et al., 2020).

The core idea of our work is to compare simulated processes with the recorded ones in the event logs when specific experiments are executed in a virtual lab. Moreover, we provide helpful information to the educator to decide if the specific virtual laboratory can be used in various educational settings. Initially, the different process models are expressed in UML Activity ADs, describing the same experiment for different educational settings. We used them because they can model composite flows and both static and dynamic aspects, needed under a virtual laboratory environment. Then they are transformed to the corresponding Petri nets, in order to apply conformance checking, since process models have to be formally defined. We used Petri nets in our approach, since the specific modeling formalism provides a long-established model of concurrency with extensive applications in modeling and analysis in various domains (Rozinat and Van der Aalst, 2008). As the proposed method just uses the simulated processes for conformance checking, it is independent of any process model notation. Based on the simulation traces of the corresponding Petri nets and real event data generated from virtual experiments execution into a specific virtual laboratory, Onlabs https://sites.google.com/site/onlabseap, a fitness index between the experiments is calculated. The term fitness is used to describe the way a Petri net and an event log are matching or aligned and is the essential element of conformance checking. The proposed method additionally returns estimation whether the same experiment in different educational settings can be executed under the specific virtual laboratory. We extended our previous work (Sypsas and Kalles, 2021) towards the direction of examining event logs from different users in the same virtual laboratory. By doing this we implemented a more comprehensive comparison, including expert users, educators and learners from different educational settings. Thus, the extra input event logs were used to validate our approach.

The remainder of the paper is organized as follows. In Section 2, the related work is summarized, while in Section 3, we briefly review the preliminaries on UML ADs, Petri nets and on conformance checking. Section 4 outlines the implementation, whistle Section 5 presents the results of the suggested approach and an acknowledgment of the limitations of the current research. Finally, Section 6 concludes by summarizing and providing a brief plan of future work.

## 2. Related work

Computing alignments was firstly applied as a conformance checking technique by Adriansyah (2014), where a depth-first search was used to detect the differences between the log traces and the system model.

Estañol et al. (2018) also applied conformance checking techniques by incorporating them into a general framework to specify business artifacts. UML state and activity diagrams were mapped into the Petri net formalism in order to apply the conformance checking technique

In the work of Taymouri and Carmona (2016) the input log trace was firstly partitioned and then using the resolution of Integer Linear Programming, a novel class of alignments is provided contributing to the exploration of model deviations. Other works mainly used Automata-based approaches to calculate the optimal alignment. In a research by Leemans, Fahland and van der Aalst (2018) the model is compared both with an event log and a model of the system under study. Based on the state space exploration of automata, Reißner, Conforti, Dumas, La Rosa and Armas-Cervantes (2017) computed all optimal alignments between system log file and the model. A different framework based on the decomposition of the given model to smaller parts was implemented in research by Munoz-Gama, Carmona and Van Der Aalst (2014). The decomposed log traces were examined and associated to each part of the initial model. Consequently, the alignment is computed for each part separately. Although this implementation is efficient it has not global alignment, since some parts may be aligned and some not.

As it turns out, the majority of the research on conformance checking relates to business processes, whereas, in the educational field, it is mainly applied to check conformance of the students behavior within a learning process (Anuwatvisit, Tungkasthan, and Premchaiswadi, 2012; Pechenizkiy, Trčka, Vasilyeva, Van Der Aalst, and De Bra, 2009). In our work, we take the distinct view that conformance checking may be applied to process models which represent virtual laboratory experiments in order to help decide if they can be deployed in educational settings for which they were not initially designed for. To our knowledge, this is the first time that conformance checking is applied to this domain.

## 3. Preliminaries

### 3.1. UML ADs and Petri Nets

A UML diagram is a partial graphical representation of a system model, mainly used for the analysis of system design, behavior and implementation. Moreover, UML AD is used to capture the flow of activities representing processes within a system. These processes may be business processes, case processes, serious educational games or experimental processes (Jena, Swain, & Mohapatra, 2014). In our approach, we used UML AD to model experiments executed in Onlabs virtual laboratory at Hellenic Open University (HOU). The specific model description refers to the recommended procedure; in the virtual laboratory. The UML AD was selected for modeling experiments for virtual lab, since the design involves scientists from different domains, such as Biology, Chemistry and Computer Science. However, the graphical representation of the behavior of a system does not support formal analysis. In this case, formal notations like Petri Nets (PN) or Automata, are preferred.

A Petri net is a dynamic structure consisted of a set containing transitions or actions that can be executed, a set of places, which are indicated by circles and may hold one or more tokens, and a set of directed arcs that connect these transitions and places with each other in a bipartite manner (Rozinat & Van der Aalst, 2008; Toguyéni, 2021). They consist a graphical and mathematical modeling tool applicable to many systems and frequently used for describing and studying information processing systems that are characterized as being concurrent, asynchronous, distributed, parallel, nondeterministic, and/or stochastic (Murata, 1989).

A PN without any initial marking is represented as a three-tuple $N = \{P, T, F\}$, where

$P = \{ p_1, p_2, \dots, p_n\}$ is a finite set of places,

$T = \{ t_1, t_2, \dots, t_n\}$ is a finite set of transitions,

$F \subseteq (P \times T) \cup (T \times P)$ is a set of arcs.

The set $(P \times T)$ represents the directed arcs from $T\ to\ P$, while set $(T \times P)$ includes the directed arcs from $P\ to\ T$, respectively. A system behavior can be described, using PN, in terms of states and their changes. A state can be changed based on the transition rules while a transition without any input place is called a source transition (initial), and the one without any output place is called a sink transition (final). Based on their properties, PN are allowing the modeling of concurrency, choices, and iteration. In order to move from UML AD to PN, a formal mapping between them needs to be implemented.

Mapping rules from ADs to PN have been proposed In research, considering modeling elements in both to be equivalent if their execution semantics are the same (Chishti, Basukoski, Chaussalet, and Beeknoo, 2018; Huang, McGinnis, and Mitchell, 2019). In the experiments implemented for HOU, there are 42 activity nodes for microscoping and 48 activity nodes for aqua solution experiment respectively, including all actions, initial and final nodes, decision nodes, join nodes and merge nodes. Based on the work of Huang et al. (2019), we implemented corresponding PNs of the experiments under study, for university and secondary education institutions. Subsequently, the formed PN models were verified and simulated, using the tool, Yasper. More information about the specific tool can be found in the following website: https://www.yasper.org/. Although the specific tool does not yet offer automatic verification of proper completion, simulation is used to all possible deadlocks, bottlenecks or any other modeling errors. Below, in Figure 2, part of the corresponding PN of an experimental procedure in HOU is shown, and in Figure 3, part of the PN for a similar experiment in secondary education is depicted.

A Workflow Net (WF-net) is a Petri net having only one start place, a single end place and every node must be on a directed path from start place to end place. The start place has no incoming arcs and the end place has no outgoing arcs. The model tasks are represented as WF-net transitions and there are no dead transitions. The experiments designed for a virtual laboratory environment, like the Onlabs in HOU, as a workflow processes, can be represented by using WF-nets.

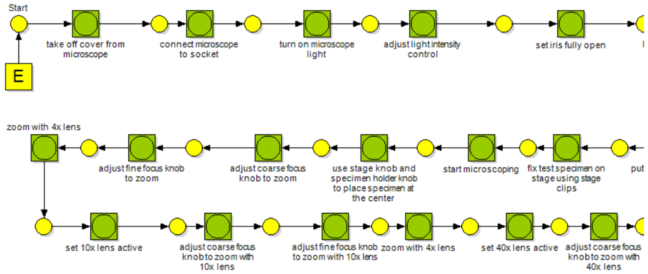


**Figure 2.** Part of the Petri net for HOU experiment

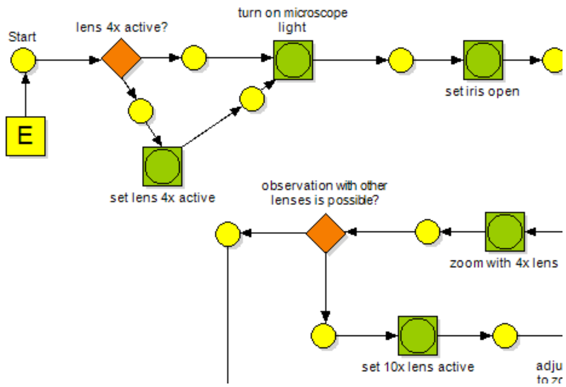
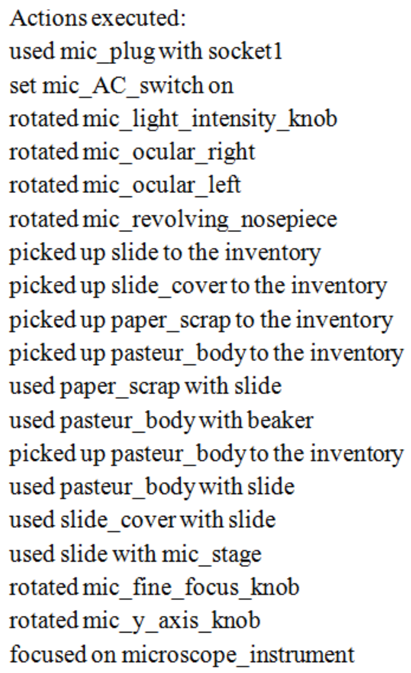


**Figure 3.** Part of the Petri net for secondary education experiment

## 3.2. Event logs

When a process is executed, the sequence of steps or activities is called *trace*. The multiset of traces is called event log and it is recorded in a log file. This multiset represents the system behavior during the execution of the specific process. The stored events refer to an experimental step during the execution under the virtual laboratory and they are totally ordered. Figure 4 shows example log for the experimental processes used for conformance checking.



```
Actions executed:
used mic_plug with socket1
set mic_AC_switch on
rotated mic_light_intensity_knob
rotated mic_ocular_right
rotated mic_ocular_left
rotated mic_revolving_nosepiece
picked up slide to the inventory
picked up slide_cover to the inventory
picked up paper_scrap to the inventory
picked up pasteur_body to the inventory
used paper_scrap with slide
used pasteur_body with beaker
picked up pasteur_body to the inventory
used pasteur_body with slide
used slide_cover with slide
used slide with mic_stage
rotated mic_fine_focus_knob
rotated mic_y_axis_knob
focused on microscope_instrument
```

**Figure 4.** Log file produced from microscoping experiment in virtual laboratory Onlabs

## 3.3. Conformance checking

Conformance checking technique is based on the alignment calculation between the stored event logs of a system and the model of the system under study. The observed (logged) and modeled behaviors are associated in order to conclude if they differ. The term alignment was defined in the work of Adriansyah (2014) as the technique discovering the best model trace that resembles a process instance, when an observed trace of representing activities is given. Additionally, all logged events that are not associated with any task in the model are removed before starting the analysis. Having in mind the above, the execution traces of the system operation are stored in an event log, and then the possible nonconformities between traces and the process model are evaluated.

In order to compute the alignment, the moves (tasks) in the process model need to be related with the moves (events) in the trace contained in the log file from experiment execution. Initially, the tasks in the model describing the experiment have to be associated with the logged events in the recorded trace. This is achieved by using a label denoting the associated log event type (if any) for each task in the model. For example, having a Petri net with labels $l$ of process model tasks/actions $t$ named as $l(t_1) = k_1, l(t_2) = k_2, l(t_3) = k_3, l(t_4) = k_4$, where $k_1, k_{2,} k_{3,} k_4$ are the logged events and a stored trace $\sigma = k_1 k_2 k_3 k_2 k_4$, possible alignments are:

$$\gamma_1 = \left| \frac{k_1|k_2|k_3|k_3}{t_1|t_2|\perp|t_3} \right|, \gamma_2 = \left| \frac{k_1|k_1|k_2|k_4}{\perp|t_1|t_2|t_4} \right|, \gamma_3 = \left| \frac{k_1|k_2|k_3|k_4}{\perp|t_1|t_2|t_3} \right|$$

The top row refers to the trace stored in the event log, while the bottom row to the process model tasks. Notation $\perp$ is used to describe the nonappearance of a model task. So, the third move in $\gamma_1$ is $(k_3, \perp)$, declares that when a trace action $k_3$ is done the process model does not move (none task is executed). So the moves in a labeled Petri net can be synchronous, when both model and log move, or asynchronous when only log moves, or only model moves, and illegal move otherwise (Rozinat and Van der Aalst, 2008). Subsequently, the fitness as part of alignment can be defined as:

$$fitness = (events\ in\ trace\ mimicked\ by\ the\ model\ ) \\ /(total\ moves\ in\ the\ observed\ trace)$$

The closer the fitness value is to 1, the more similar the model is to the event log file. When none of the model task occurs in the log file the metric value is 0. On the contrary, when every task occurs at least once in the log the metric value is 1.

Expressing a WF-net as $N$, the initial marking of the net as $m_{start}$ and the final marking of the net as $m_{end}$ the tuple $SN = (N, m_{start}, m_{end})$ represents a system net (Taymouri and Carmona, 2020). The full firing sequences of SN generate the set $\{\sigma | (N, m_{start})[\sigma > (N, m_{end})\}$. Then, the fitness metric defined above, can be expressed as: A trace $\sigma \in \Sigma^*$ fits $SN = (N, m_{start}, m_{end})$ if $(N, m_{start})[\sigma > (N, m_{end})$, where $\Sigma$ is an alphabet of events and a trace is a word $\sigma \in \Sigma^*$.

## 4. Implementation

The alignment calculation as the main part of conformance checking technique is used to compare the traces of virtual laboratory log file and the PN of the same experiment in secondary education. As a result, we conclude about the possible use of the same virtual laboratory in different educational settings.

As a first step in our approach, the experiments for university and secondary education level are modeled using UML ADs and the corresponding WF-nets. Then, they are run and a finite set of simulation traces is produced. In order to compute fitness for alignment, we produce the log file by running the simulation of university experiment in virtual laboratory. Thus, the recorded log file contains the ordered tasks for HOU experimental procedure. These traces are stored in a called simulation log file and will be used for fitness computation between models. Successively, the experiments are executed in the virtual laboratory from different users (expert users, teachers and students) and the produced logs are recorded. The tasks in the process model are associated with the logged events. The mapping results are stored in an association database, containing associated model events and logged traces. In the previous step, the mapping between the model trace and logged events is achieved. This mapping is used in order to compute the fitness between the model of the experiment in secondary education and the logged trace from execution of the experiment modeled. Fitness results are calculated for the log files produced from the different users, contributing to conclude whether the same virtual laboratory can be used with or without further investigation for the execution of the experiment in a different educational setting. The figure 5 below depicts the implementation framework.

## 5. Results and Discussion

The implemented approach was applied on the experiment of microscopy, which is essential part of the laboratory biology education both for university and secondary education level. When the university experiment was executed in virtual laboratory by a secondary education student, the calculated alignment was quite successful, as a total of 22 actions of the process model for secondary education occurred in the log file in a total of 36 logged events, giving $fitness = 0{,}62$. In order to validate the result, we asked from external users to execute the same experiment under the same virtual laboratory. These were 1 expert user, 2 teachers from secondary education (1 biology and 1 chemistry teacher), 2 students from upper secondary education (Lyceum) and 2 students from lower secondary education (Gymnasium). Since the experimental process was not guided from the software, users followed the experimental steps at their own will. The results of these executions are shown in Table 2.

**Table 1.** Fitness calculation for different users on microscoping

| User | Fitness |
|---|---|
| Expert user1 | 0.77 |
| Teacher1 (Biology) | 0.75 |
| Teacher2 (Chemistry) | 0.72 |
| Upper Secondary Education student1 | 0.68 |
| Upper Secondary Education student2 | 0.69 |
| Lower Secondary Education student1 | 0.62 |
| Lower Secondary Education student1 | 0.61 |

Based on the results, the majority of the process model tasks for the experiment in secondary education are contained in the logged events produced by the experiment execution in the virtual laboratory designed for university use. However, some of the model tasks are in different order, so some alignment may be necessary. For example, the decision node of whether lens 4x is active in the microscope is in different order between the model event for secondary education experiment and the logged trace from university experiment. Still, the general learning outcome (manipulate microscope lenses), which is set by the educational program, it can be said that is achieved. Having in mind the fitness calculation, the concluding learning outcome achievement decision depends on the educator's opinion. Although, the fitness calculation discovered that the expert user and the teachers executed the given experiment in a way that is close to the process model, students from various educational settings achieved rather small fitness. Hence, the above alignment calculation results revealed that the microscoping experiment in secondary education can be executed using the same virtual laboratory used for university level. This aligns with the results of the research from Sypsas and Kalles (2021). Summarizing, when our proposed approach is applied, the secondary education learners can gain access to educational tools and educational benefits used mainly for distance education in university settings. In case, the educator may decide whether the experimental steps need to be changed to meet the learning outcomes, the process model is modified to depict these changes in order to achieve the specific learning outcomes.

Of course, there still exist limitations. Even though the users for validation check are from different educational settings and areas of expertise, the promising results of our research must be seen under the lens of the limited application of our approach on a single experiment. Therefore, further research concerning other experiments executed in various educational settings must be carried out.

## 6. Conclusions

Conformance checking in the context of Educational Process Mining is mainly used to detect deviations between expected model behavior and actual model execution. Therefore, actual stored log files of the investigated system are used to compute a similarity index, by aligning the model of an experiment in a specific educational level to the logged file produced from simulation of the same experiment in a different educational level.

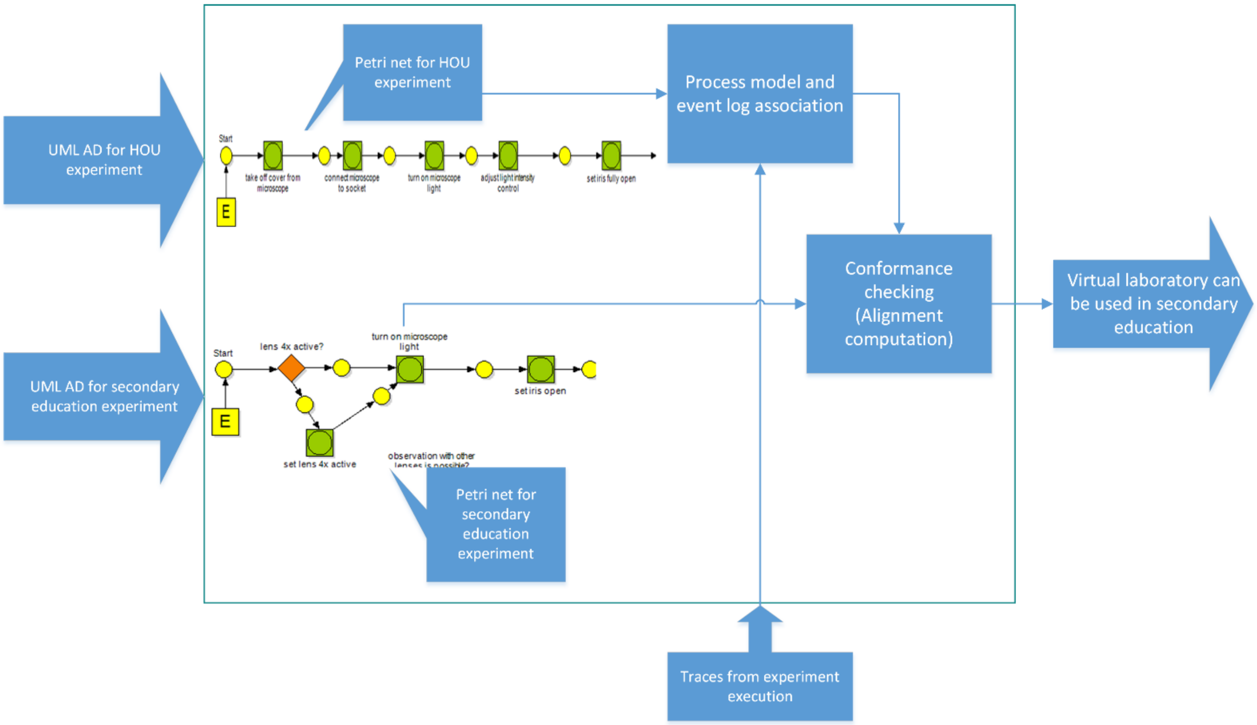


**Figure 5.** Implementation framework for Conformance Checking application

We have presented a framework to assist educators in making a decision about the use of a specific virtual laboratory in an educational setting which is different from the one which inspired the original Virtual Laboratory development. We implemented the application of alignment technique on the process model for secondary education experiment and the logged data from experiment execution in a virtual laboratory for university. Finally, our approach was applied by various users from different educational settings and the results revealed good performance in well-defined experiments, concluding whether they can be executed in the same virtual laboratory environment without further investigation.

In order to tackle the limitations of our present study, we are using the proposed approach for validation on other experiments which are commonly executed in a variety of educational settings, all with possible changes between them (the actual experiment we are working on is the production of an aqueous solution). Moreover, we are working on the virtual laboratory simulator recommendation system, depending on the user profile. We expect that the integration of those two research directions will provide a more thorough learning toolkit to educators and learners alike, in a variety of educational settings.

## Acknowledgements

The text of this paper contains information and generic descriptions from some other work (properly referenced) by the same co-authors. The paper contains considerable new information in sections 2, 5 and 6, which constitutes new work.

## References

Adriansyah, A. (2014). *Aligning Observed and Modeled Behavior*. Technische Universiteit Eindhoven. https://doi.org/10.6100/IR770080

Anuwatvisit, S., Tungkasthan, A., & Premchaiswadi, W. (2012). Bottleneck mining and Petri net simulation in education situations. In *International Conference on ICT and Knowledge Engineering* (pp. 244–251). https://doi.org/10.1109/ICTKE.2012.6408562

Atanasijević-Kunc, M., & Karer, G. (2021). Modelling and simulation : adaptation of educational processes to epidemic measures. In *33rd European Modeling & Simulation Symposium* (pp. 99–106). https://doi.org/10.46354/i3m.2021.emss.014

Bogarín, A., Cerezo, R., & Romero, C. (2018). A survey on educational process mining. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, *8*(1), e1230. https://doi.org/10.1002/widm.1230

Cairns, A. H., Gueni, B., Hafdi, H., Joubert, C., & Khelifa, N. (2015). Towards a distributed computation platform tailored for educational process discovery and analysis. In *International Conference on Protocol Engineering, ICPE 2015 and International Conference on New Technologies of Distributed Systems, NTDS 2015 - Proceedings* (pp. 1–8). https://doi.org/10.1109/NOTERE.2015.7293494

Chishti, I., Basukoski, A., Chaussalet, T., & Beeknoo, N. (2018). Transformation of UML activity diagram for enhanced reasoning. In *Proceedings of the Future Technologies Conference (FTC)* (Vol. 881, pp. 466–482). Vancouver, Canada. https://doi.org/10.1007/978-3-030-02683-7_33

Estañol, M., Munoz-Gama, J., Carmona, J., & Teniente, E. (2018). Conformance checking in UML artifact-centric business process models. *Software and Systems Modeling*, *18*(4), 2531–2555. https://doi.org/10.1007/s10270-018-0681-6

Fani Sani, M., van Zelst, S. J., & van der Aalst, W. M. P. (2020). Conformance Checking Approximation Using Subset Selection and Edit Distance. In S. Dustdar, E. Yu, C. Salinesi, D. Rieu, & V. Pant (Eds.), *Advanced Information Systems Engineering* (pp. 234–251). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-49435-3_15

Ghazal, M. A., Ibrahim, O., & Salama, M. A. (2017). Educational process mining: A systematic literature review. In *Proceedings - 2017 European Conference on Electrical Engineering and Computer Science, EECS 2017* (pp. 198–203). IEEE. https://doi.org/10.1109/EECS.2017.45

Huang, E., McGinnis, L. F., & Mitchell, S. W. (2019). Verifying SysML activity diagrams using formal transformation to Petri nets. *Systems Engineering*, *23*(1), 118–135. https://doi.org/10.1002/sys.21524

Jena, A. K., Swain, S. K., & Mohapatra, D. P. (2014). A novel approach for test case generation from UML activity diagram. *Proceedings of the 2014 International Conference on Issues and Challenges in Intelligent Computing Techniques, ICICT 2014*, 621–629. https://doi.org/10.1109/ICICICT.2014.6781352

Leemans, S. J. J., Fahland, D., & van der Aalst, W. M. P. (2018). Scalable process discovery and conformance checking. *Software and Systems Modeling*, *17*(2), 599–631. https://doi.org/10.1007/s10270-016-0545-x

Murata, T. (1989). Petri Nets : Properties , Analysis and Applications. *Proceedings of the IEEE*, *77*(4), 541–580.

Pechenizkiy, M., Trčka, N., Vasilyeva, E., Van Der Aalst, W., & De Bra, P. (2009). Process mining online assessment data. In *EDM'09 - Educational Data Mining 2009: 2nd International Conference on Educational Data Mining* (pp. 279–288).

Reißner, D., Conforti, R., Dumas, M., La Rosa, M., & Armas-Cervantes, A. (2017). Scalable conformance checking of business processes. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *10573 LNCS*, 607–627. https://doi.org/10.1007/978-3-319-69462-7_38

Rozinat, A., & Van der Aalst, W. M. (2008). Conformance Checking of Processes Based on Monitoring Real Behavior. *Information Systems*, *33*(1), 64–95. Retrieved from http://www.mathcces.rwth-aachen.de/_media/3teaching/0classes/archiv/080_ces_seminar_conformancechecking.pdf

Sypsas, A, & Kalles, D. (2021). Computing Similarities Between Virtual Laboratory Experiments Models using Petri Nets. In *20th International Conference on Modelling and Applied Simulation, MAS 2021* (pp. 29–37). https://doi.org/10.46354/i3m.2021.mas.004

Sypsas, A., & Kalles, D. (2022). Reviewing Process Mining Applications and Techniques in Education. *International Journal of Artificial Intelligence & Applications (IJAIA)*, *13*(1), 83–102. https://doi.org/10.5121/ijaia.202213106

Taymouri, F., & Carmona, J. (2016). A recursive paradigm for aligning observed behavior of large structured process models. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *9850 LNCS*, 197–214. https://doi.org/10.1007/978-3-319-45348-4_12

Taymouri, F., & Carmona, J. (2020). Computing Alignments of Well-Formed Process. *ACM Transactions on Software Engineering and Methodology*, 29(3), 1–41. https://doi.org/10.1145/3394056

Toguyéni, A. (2021). Synthesis of Petri Nets based controllers for the automation of train routing in a railway node. In *20th International Conference on Modelling and Applied Simulation, MAS 2021* (pp. 176–185). https://doi.org/10.46354/i3m.2021.mas.022

Trčka, N., Pechenizkiy, M., & van der Aalst, W. (2010). Process mining from educational data. In C. Romero, S. Ventura, M. Pechenizkiy, & R. Baker (Eds.), *Handbook of Educational Data Mining* (Chapman &, pp. 123–142). CRC Press. https://doi.org/10.1201/b10274

Tsoni, R., Stavropoulos, E. C., & Verykios, V. S. (2019). Leveraging Learning Analytics with the Power of Words. *The Envisioning Report for Empowering Universities*, 24, 24–26.

Van Der Aalst, W. (2012). Process mining. *Communications of the ACM*, *55*(8), 76–83. https://doi.org/10.1145/2240236.2240257

van Zelst, S. J., Bolt, A., Hassani, M., van Dongen, B. F., & van der Aalst, W. M. P. (2017). Online conformance checking: relating event streams to process models using prefix-alignments. *International Journal of Data Science and Analytics*, *8*(3), 269–284. https://doi.org/10.1007/s41060-017-0078-6