Petri nets for adaptive learning scenarios in serious games

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Abstract

Serious games are becoming a more commonly utilized tool in training, education, and learning. On the other hand, Petri nets, a well-known formalism for process modeling, seem to be a promising tool for describing learning activity scenarios for serious games and virtual environments. Thanks to their graphical form and easy-to-understand nature, it can be assumed that participants from different backgrounds should be able to understand and use Petri nets for their scenarios. A present study presented here investigates how this assumption corresponds to reality. In the study, a short explanation of Petri nets and a set of related tasks were given to a sample of 31 participants (n = 31). The participants were students of Computer Science (16) and Humanities (15). The results collected and statistically analyzed demonstrate both similarities and distinctions in the reactions to problem-solving assignments among individuals in the two groups. These findings and their analysis have been condensed and presented in visual form.

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General Terms: Serious Games, Virtual environment, Petri net, Scenarios, Participants.
Additional Key Words and Phrases: Implementation, Modeling education, Learning,

1. INTRODUCTION

Serious games (SGs) have already played a crucial role in training, coaching, and education in various fields throughout history. Earlier, Abt (1970) defined the term "serious" as being used within the context of a study that pertains to matters of significant interest and importance. Such studies typically raise questions that are complex and not easily resolved, with potential consequences that merit careful consideration. In connection with the foregoing, serious gaming involves applying game concepts for learning, skill development, and training (Cain et al., 2015; Asadzadeh et al., 2024). Development or training through SGs could be of different purposes like the one based on virtual and mixed reality (Kadri et al., 2024; Zhang et al., 2023; Altan et al., 2022; Pournajaf et al., 2022; Richard et al., 2021), simulation (Beňo et al., 2021) or how citizens understand and perceive possible inequalities related to urban mobility (Vecchio, 2024; Wang et al., 2023). Furthermore, SGs can

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be an effective teaching and learning tool for students of all ages and in many situations because they are highly motivating and because they effectively convey concepts and facts from many subjects. SGs offer extensive possibilities for not only technical, social, or natural sciences education but also extend to the humanities and medicine. Additionally, SGs serve as effective tools for training, coaching, and enhancing specialized areas or focuses. Ultimately, the goal of SGs is to improve the skills, abilities, and knowledge of students, teachers, and staff members. Unlike conventional games, SGs are created for education and training. Talebi Azadboni et al. (2024) discuss SGs among the tools at teachers' disposal; using SGs to teach different skills has proven to be a particularly effective educational strategy.

There is a wide range of approaches, strategies, or methodologies that can be applied in the development of SGs. One of the approaches, that can be applied is based on the implementation of Petri Nets (PNs). This approach is based on the principle of decoupling the graphical-visual environment from the gameplay of a serious game. As a result, players are allowed to customize the gameplay according to their preferences. This allows each player to achieve a different gameplay.

Petri (1962) defined these nets as a diagrammatical mathematical modeling language for describing the behavior of discrete event systems. Silva (2013) shows that one of the main advantages of PNs as a tool of implementation is their simple graphical notation that makes it easy to describe systems or processes that are concurrent and non-deterministic. The PNs can be applied in many fields such as *manufacturing*: implemented as a model for creating hybrids of PNs, cellular automata, and neural network-driven deep learning models to enhance the scope and quality of modeling and simulation in smart manufacturing (Kaikova et al., 2024; Grobelna et al., 2021), *e-business*: improving security in e-commerce procedures for logical vulnerability detection (Yu et al., 2024), *Internet of Things* (IoT): integration of high-level PNs with IoT-based devices for improved decision-making and behavior control (da Silva Fonseca et al., 2023), *household environments*: modeling and control in higher control levels by proposing an approach that uses PNs to optimize energy in household environments (Balogh et al., 2023) or *analysis methods:* PNs can be oriented for analysis methods based on the coverability multigraph (Hrúz et al., 2014) and many other fields.

One of the prospective fields of PN utilization is extended reality (XR) environments. Margetis et al. (2019) state that XR - that is augmented, virtual, and mixed-reality - technologies have transitioned from research labs to become widely accessible to the general population. Korečko et al. (2022) show that extended reality has been quite frequently used in education, offering virtual environments (VE) to improve knowledge and understanding across different subjects. They also propose to utilize PNs as a tool for defining scenarios of such educational VE. The motivation behind this proposal is a belief that thanks to their easy-to-understand nature, educators of different backgrounds can use PN for defining their own VE scenarios.

The paper is organized as follows. Section 1 introduces and characterizes the topic of SGs and PNs from a general point of view, as well as from the point of view of their use in education. Section 2 describes and explains the related work and Section 3 presents the methodology, including the research design, participants, material, and procedure. In Section 4, we show results of understanding of PN-related tasks in potential utilization for SGs. Section 5 lists the limitations of the study, and the paper concludes with Section 6.

2. PREVIOUS WORK

Many research studies have used PNs to model and evaluate asynchronous systems and competitors (Thomas et al., 2011). However, only scarce research exists regarding the utilization of PNs in SGs and there is even less research on modeling the learning process of the SG.

Thomas et al. (2011) discuss developing an approach based on PNs, which authors used to model the accurate behavior of the player. This approach, which is implemented in SGs, is focused on business training by analyzing and diagnosing the knowledge acquisition of the learner while authors monitor a player's learning progress. Liang et al. (2023) developed and integrated the learning-embedded attribute PNs (LAPN) model to represent game flow and student learning decision-making. The designed model was demonstrated in the example of SG Gridlock. On the other hand, the research by Korečko et al. (2022) was focused on introducing a model that combines scenarios, created with a specific type of PNs known as Place/Transition nets, with virtual 3D environments accessible online through a web browser. This approach was verified by a prototypical VE, containing a historical exposition capturing the Enlightenment era in the Habsburg monarchy. With the results of the study, the authors show the most important goal of the approach was to have the ability to change the scenario and define the user's actions without the need to re-design or re-program the virtual environment. Hare et al. (2022) introduce a framework for personalized student assistance within adaptive SGs using reinforcement learning and PNs. In conclusion, this shows that their hierarchical reinforcement learning approach outperforms traditional methods. They also demonstrate that the proposed hierarchical reinforcement learning approach offers significantly improved training performance over a tabular, single-agent approach. In the work of Yamaguchi et al. (2017) authors focused on proposing a PN model of stalkers' behavior, while they applied the game in a high school. Afterward, they proposed an SG focused on the simulated experience of stalkers, while the target group was students at high school. As a result of the study, 75% of the students changed their attitude and perception about the stalking problem. Sinclair et al. (2016) examine combining the complementary strengths of PNs and SGs. The authors prepared an SG prototype of a complex system design; while based on PN analysis, the SG can be used as a high-level interface to communicate and refine the design. Another use of PNs is offered by Gieseking et al. (2021), who present a web interface that allows an intuitive, visual definition of PNs with transits and Petri games. The model focuses on checking and synthesis problems, which are addressed on a server, allowing for analysis and simulation of implementations, counterexamples, and all intermediate steps in the interface.

3. METHODOLOGY

This section of the study provides some description of the research design, description of the research sample of participants, materials, and procedures, utilized in the study (with the tasks assigned to participants and the evaluation procedure).

3.1. Research Design

As mentioned above, one approach in the development of SGs can be based on implemented PNs. Based on this, the objective of the study was formulated. The study aimed to investigate differences in participants' understanding of processes (via 3 tasks) based on the use of PNs designed to modify virtual learning environments implemented in SGs.

3.2. Participants

The research sample consisted of a total of 31 participants (15 females and 16 males). It can be divided into two groups: computer science (with mean age of 20.4 years; range 19 – 23 years) and humanities (with mean age of 19.8 years; range 19 – 21 years). From 31 participants, 2 participants decided prior to completing the test to stop and exit the study (1 male and 1 female). The reasons for the non-completion of the test by two participants were not provided. Consequently, their data were excluded from the analysis to maintain the integrity of the research. Participants were studying in the 1st year of their bachelor's degree at a public university in Slovakia. From the research sample (31 participants), 28 were Slovaks, 2 were Ukrainians, and 1 participant was Japanese. Most of them were residents of a city (17), with the remaining 14 being residents of a village. Before the study started, it was approved by the faculty board. The participants completed the questionnaire voluntarily and were unpaid. In addition, they were asked by the first author to participate in the study. At the beginning of the session, they were instructed about the study process (to complete the survey, solve the tasks, etc.).

3.3. Materials and Procedure

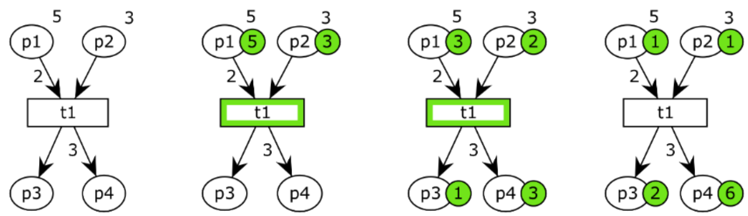
At the beginning of the research study, participants were asked to complete a survey. Two participant groups were involved in the study: computer science students (who completed the survey online) and humanities students (who completed the survey using paper and pencil). The survey contained 16 items. These items were focused on demographics including their educational background, whether the participants had ever meet with the term of PNs, and if so, whether they understood the basic principles, if they have any experience with process graphs, and whether they were currently employed part-time. The primary purpose of the questionnaire was to gather data that could potentially be correlated with various tasks within the study.

After that, the study procedure consisted of two parts. In the first one, PNs were explained to the participants. In the second part, the participants were given several tasks to accomplish. Among them, 3 tasks, T.1.1 to T.1.3, were about adding arcs to a graph of a PN with all the vertices (places and transitions) already there. Data were collected in the spring 2024. Each group of participants completed the study in one session. Each participant was asked to draw the solutions for each task.

3.3.1 Explanation

In about 40 minutes, the basics of PN and their utilization for scenarios were explained to the participants, using four examples (Ex.1 to Ex.4) and the CPN tools software, an editor, and simulator for PN. In addition, a printed form of the explanation with the same examples was given to each participant to refer to when accomplishing the tasks.

Ex.1



a) *b)* *c)* *d)*

Fig. 1. Petri net Ex.1: graph only (a) and the net in all its markings from the initial to the final one (b-d). In (b-d), the enabled transition has a green outline, and the actual marking is shown in the green-filled circles.

First, the basic principles of PN were presented on the net Ex.1 (Figure 1). The presentation was purely practical, formal definitions were left out. We explained that a PN is a bipartite oriented graph. The two types of vertices are places, drawn as ellipses (p1, p2, p3, p4 in Figure 1), and transitions, drawn as rectangles (t1 in Figure 1). Each place may hold 0 or more tokens and the number of tokens in a place is called a marking of the place. The markings of all places of a net form the marking (state) of the whole net. Each PN has an initial marking, defined by numbers written next to places. For the net in Figure 1, it is 5 tokens in p1, 3 in p2, 0 in p3, and 0 in p4. Next, we explained that a net advances from one marking to another by firing (executing) its transitions and that only transitions enabled in a given marking can be fired. There are 3 reachable markings for the Ex.1 net, as shown in Figure 1 b) to d). A transition is enabled if and only if there are enough tokens in each place from which an arc leads to it. Enough means equal to or more than the weight of the corresponding arc. If there is a number written next to an arc, its weight is the value of that number. If there is no number, the weight is equal to 1. In the initial marking of the Ex.1 net (Figure 1 b), t1 is enabled as 5>2 and 3>1. How a transition firing changes the marking is defined by the direction and weight of the adjacent arcs. Therefore, a firing of t1 in the initial marking of the Ex.1 net takes 2 tokens from p1, 1 from p2, and adds 1 token to p3 and 3 tokens to p4, resulting in the marking shown in Figure 1 c). After another firing of t1, we reach a final marking, where no firing is possible as there is only one token in p1 (Figure 1 d).

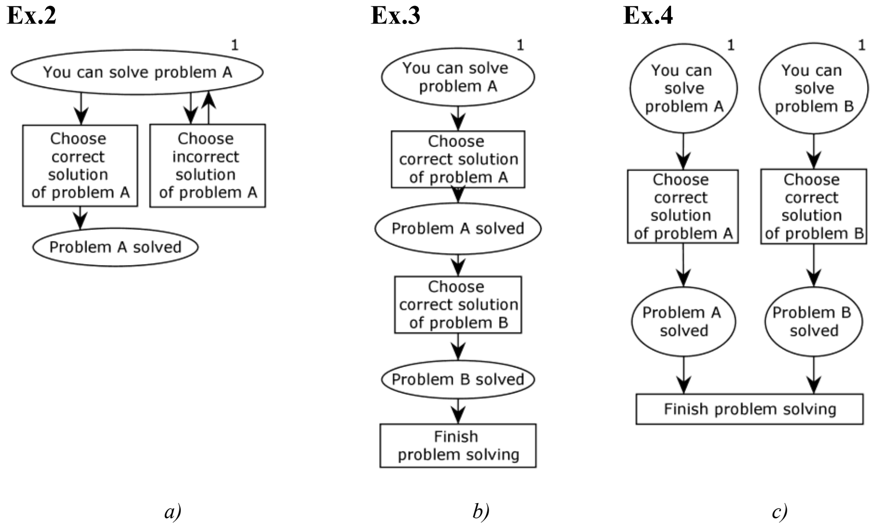


Fig. 2. Petri nets for simple learning activity scenarios: Ex.2 to address the issue of potentially perpetuating an incorrect solution indefinitely (a), Ex.3 for solving 2 problems in a sequence (b) and Ex.4 for solving 2 problems in parallel or regardless of the order (c). The possibility to choose an incorrect solution is not considered in Ex.3 and Ex.4.

The net Ex.1 does not have any particular meaning. The remaining examples Ex.2, Ex.3, and Ex.4 (Figure 2) show some basic cases that may occur in learning activity scenarios for virtual environments. The meaning of these example nets was explained in detail and all the reachable markings were shown, both in CPN Tools and in the printed form (in the same fashion as Figure 1 b-d). At the end of the explanation, we remarked that we deal with only one of many dialects of PN here and that not all PN have final markings (i.e. there may always be some transitions to fire).

3.3.2 Tasks

After the explanation and subsequent short discussion, the participants were given the tasks. The assignment for each of the tasks T.1.1 to T.1.3 described what the corresponding net should do and presented an incomplete graph of the net with vertices only. There also was a reminder that place-to-place and transition-to-transition arcs are forbidden and a hint, specific for a given task. In these tasks, the participants had to add arcs.

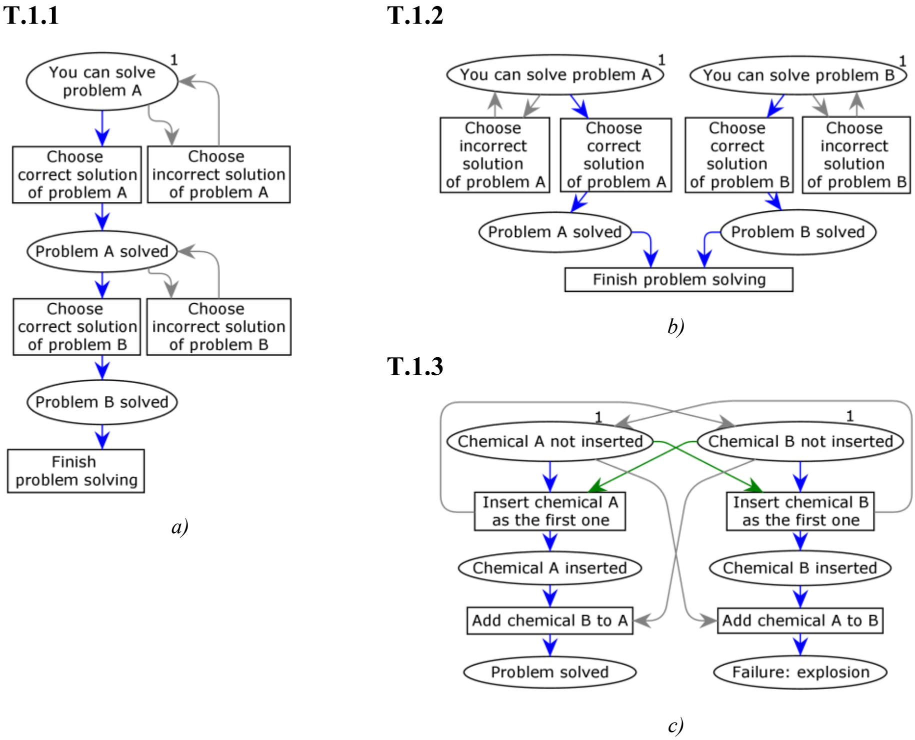


Fig. 3. Petri nets representing solutions to tasks T.1.1 (a), T.1.2 (b) and T.1.3 (c). The correct solutions consist of all the arcs depicted. The blue-colored arcs form partially correct solution cores. In c), the blue- and green-colored arcs form an almost correct solution (level 9).

The goal of the first task, T.1.1 was to complete a PN representing a learning scenario, where a student deals with 2 problems, A and B. The problems should be solved sequentially, A first, B second. The incorrect solution can be chosen repeatedly, without any limitations. Problem B can be attempted only after problem A is solved successfully. After successfully solving both problems, the "Finish problem-solving" transition should be fired. The hint for T.1.1 was to examine the example nets Ex.2 and Ex.3 for inspiration. The correct solution of the task is shown in Figure 3 a). Task T.1.2 differs from T.1.1 in that it doesn't matter which problem is solved first and the hint is to look at the example nets Ex.2 and Ex.4. The solution for T.1.2 is in Figure 3 b).

Task T.1.3 is slightly different. It is about a specific problem, namely the mixing of two chemicals. The correct way is to insert chemical A first and then add chemical B.

This leads to success, represented by a token in the place "Problem solved". Mixing the chemicals in the opposite order leads to an explosion, i.e. a token in the place "Failure: explosion". The hint was that in two cases a pair of arcs connecting a place and a transition in both directions should be used.

3.3.3 Task solutions evaluation

To evaluate the task solutions, a scale from 0 to 10, where 0, 5, and 10 are the key levels and the other numbers represented in-between levels, was used.

Table I. Key levels for the task evaluation

Level	***Meaning***
10	Correct solution (as in Figure 3).
5	Solution core (as blue arcs in Figure 3).
0	No or completely meaningless solution or place-to-place or transition-to-transition arcs.

The key levels are explained in Table I. The solution cores are partially correct solutions that capture the essence of the corresponding processes. As it can be seen in Figure TSK (blue arcs), the core for T.1.1 is equal to the net Ex.3, T.1.2 to Ex.4. For T.1.3, the core contains processes for correct and incorrect mixing of chemicals, but without any connection between them.

Table II. In-between levels for the task evaluation

Level		***Meaning***
9	4	Only the correct sequences of transition firings are possible, but some markings are inconsistent with the names of the places.
8	3	An omission or carelessness prevents the correctness.
7	2	Approximately half of the new functionality is present and working correctly.
6	1	A reasonable attempt to go for the next higher key level, but not even half of a new functionality is present and working correctly.

The in-between levels form two similar groups, 6 to 9 and 1 to 4. They are described in Table II, where the correctness is understood with respect to the nearest higher key level (i.e., 10 or 5) and the new functionality is new with respect to the nearest lower key level (i.e., 5 or 1).

4. RESULTS AND DISCUSSION

In this section we present and illustrate the findings, results, and discussion of the study, focusing on the understanding of PN-related tasks in potential utilization for SGs. As indicated in Table III, the study included a cohort of 31 participants. From this research sample, 16 participants were studying computer science (15 males and 1 female). In the Table III, we refer to them as "C01 - C16". The remaining 15 participants were students of humanities (1 male and 14 females) and were identified as "H01 - H15" (Table III).

Table III. Study results for participants belonging to the computer science students on the left (C01 to C16) and humanities students on the right (H01 to H15). The column labels have the following meaning: Resp. – participant id, Gender – (M)ale or (F)emale, Grd.IT – graduated from IT – (Y)es or (N)o, PrG.U and PN.U – understanding of process graphs and PN (LIKERT-5 scale), T.1.1 to T.1.3 – evaluation of individual tasks.

Resp.	***Gender***	***Grd.IT***	***PrG.U***	***PN.U***	***T. 1.1***	***T. 1.2***	***T. 1.3***
C01	M	Y	3	1	10	10	2
C02	M	Y	2	1	7	10	9
C03	M	Y	2	3	7	6	9
C04	M	Y	4	2	10	10	9
C05	M	Y	1	1	10	10	9
C06	M	Y	3	2	10	8	5
C07	M	Y	3	2	10	10	2
C08	M	Y	2	1	10	10	5
C09	M	Y	3	1	5	7	1
C10	M	N	3	3	10	10	1
C11	M	Y	3	1	10	10	9
C12	M	N	5	5	10	10	9
C13	M	Y	3	3	7	8	1
C14	M	N	3	3	10	10	2
C15	M	N	2	2	10	10	3
C16	F	Y	1	3	10	10	3

Resp.	***Gender***	***Grd.IT***	***PrG.U***	***PN.U***	***T. 1.1***	***T. 1.2***	***T. 1.3***
H01	F	N	1	1	10	6	1
H02	F	N	1	1	10	6	1
H03	M	Y	3	3	10	6	9
H04	F	N	1	1	7	6	2
H05	F	N	1	1	7	7	0
H06	F	N	1	1	10	8	5
H07	F	N	1	1	10	10	2
H08	F	N	1	1	6	8	1
H09	F	N	1	1	10	3	2
H10	F	N	1	1	8	10	1
H11	F	N	1	1	10	10	1
H12	F	N	1	1	7	6	1
H13	F	N	1	1	7	6	1
H14	F	N	1	1	7	6	1
H15	F	N	1	1	10	6	5

We evaluated individual solutions of the tasks T.1.1, T.1.2, and T.1.3 of each participant from both groups. In addition, for each participant we collected demographic data consisting of their gender, age, place of residence as well as graduation from the field of informatics (Grd.IT), and how well the participants understood the problem of process graphs (PrG.U, answered on Likert scale, rating from 1 to 5, with 1-excellent and 5-not at all). Furthermore, we asked the participants whether they were familiar with the concept of PNs (PNrG.U) - in this case, a 5-point Likert scale was used, with the participant having the option to choose definitely no (1), rather no (2), both yes and no (3), rather yes (4), and definitely yes (5).

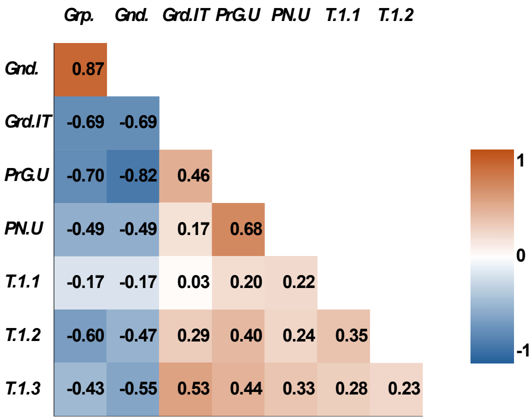


Fig 4. Correlation heatmap for the individual parameters of the study results. “Grp.” means a group of students, i.e. computer science or humanities. Other labels are as in Table III.

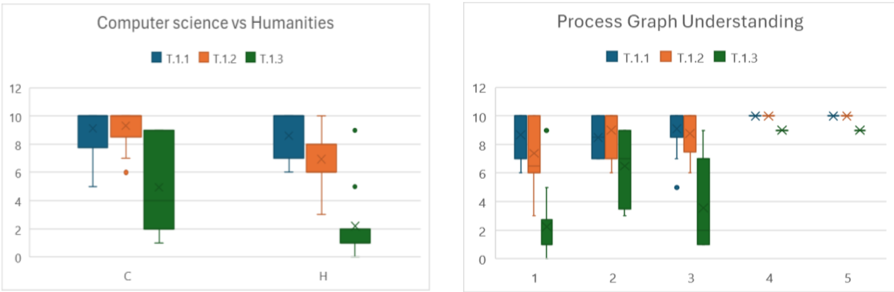
We conducted a correlation analysis (Figure 4) to examine the relationship between the data collected about the participants and their performance in the task solving. The strongest correlation (0.87) is between the gender (Gnd.) and the group (Grp.). This is completely natural given the distribution of gender over the groups in the sample. The group and gender also very strongly or almost very strongly correlate with the self-perceived level of understanding process graphs (Prg.U) and the presence of graduation from information technologies (Grd.IT). Regarding the task solutions evaluation (T.1.1, T.1.2 and T.1.3), the correlation increases with the rising difficulty of the task in almost all cases. This is the most evident in the case of Grd.IT, where the IT graduation has little to no influence (0.03) on the performance in T.1.1, almost moderate (0.29) in T.1.2 and strong (0.53) in T.1.3. Regarding the other data collected, the situation with respect to the task solution is similar but the correlation for T.1.1 is higher (around 0.2) and Grp has higher correlation with T.1.2 than T.1.3. This can be contributed to the participants C11 and H03, who reached level (score) 9 in T.1.3 but differ from the other high-scoring participants in Grp. or Grd.IT.

Considering the strong to very strong correlation between the group, gender, process graph understanding and IT graduation, we chose the group affiliation as the main factor when examining the results further.

Table IV. Achieved task solution level (score) statistics for the computer science and humanities groups.

	Computer science			***Humanities***		
	T.1.1	***T.1.2***	***T.1.3***	***T.1.1***	***T.1.2***	***T.1.3***
Avg	9.13	9.31	4.94	8.60	6.93	2.20
Median	10.00	10.00	4.00	10.00	6.00	1.00
Mode	10.00	10.00	9.00	10.00	6.00	1.00
StDev	1.63	1.30	3.45	1.59	1.94	2.37
Max	10.00	10.00	9.00	10.00	10.00	9.00
Min	5.00	6.00	1.00	6.00	3.00	0.00

As Table IV shows, success rates for the tasks T.1.1 and T.1.2 were higher compared to the task T.1.3. In T.1.1, computer science participants scored an average of 9.13, while humanities participants scored 8.60, resulting in a statistically insignificant difference of 0.53. In T.1.2, the scores differed between the two groups: while computer science scored 9.31, the humanities participants scored 6.93 and the difference was 2.38. This represents a slightly larger difference compared to T.1.1. However, T.1.3 showed the biggest disparities between the groups, with computer science participants scoring 4.94 and humanities participants scoring 2.20, resulting in a difference of 2.74. No statistically significant differences were found between the minimum and maximum score values.



a) b)

Fig. 5. Correspondences and differences in solutions of tasks T.1.1, T. 1.2 and T.1.3 with respect to the group affiliation (a) and the process graph understanding (b).

The differences are also evident from the box and whisker plots in Figure 5. While the performance in T.1.1 and T.1.2 is similar, especially in the computer science group, the performance drop regarding T.1.3 is evident everywhere. The highest performance in T.1.3 was achieved by those participants that evaluated themselves as very familiar with the process graphs (Figure 5 b). From the results presented, we can consider the comprehension rate differences of the Petri net processes between tasks T1.1 and T1.2 as not statistically significant. In contrast, the differences for Task T1.3 were statistically significant.

These findings suggest that, as the task difficulty rose, the differences between the two groups increased. The larger disparities in task T1.3 may be attributed to insufficient understanding of PNs due to the limited explanation time, or a greater emphasis on visual rather than functional aspects of problem-solving by humanities participants.

5. LIMITATIONS

In this paper, we present a study aimed at investigating the understanding of PNs in the context of their application in SGs. The study also compares the task-solving performance between two distinct participant samples.

At the beginning of the study, we gave a short explanation of PNs and a set of related tasks to two groups of students. Both groups of participants consisted of computer science and humanities students. Based on the results, it can be concluded that there is a possibility to implement PNs in SGs to define so-called scenarios of learning virtual environments (VEs). Our goal is to achieve the use of PNs to define customized VE scenarios targeting different learning domains.

Based on the data obtained from the study, it can be concluded that the results from the solved tasks T.1.1 and T.1.2 were comparable. On the other, hand there was a significant difference between participants regarding T.1.3: computer science participants scored higher than the humanities. In addition, none of the participants achieved 100% correct solution.

From the perspective of future research, we will aim to replicate the above study after making several modifications identified from the results of the one presented here. In addition, the research sample size of participants will be expanded and will focus on teachers from teaching practice of different subjects.

6. CONCLUSIONS AND FUTURE WORK

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