A system of digital simulation models for distance learning of computer subsystems in IT courses

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Abstract. Modern education actively uses new forms, such as distance learning, information technology, including the use of digital models. In the article, a system of digital software models to simulate the basic components of modern computers is considered. The described system is focused on the study of the composition and processes in the computer in IT courses for university students. The structure of system simulation models are designed for the study of the groups of the main computer subsystems: input/output subsystem, cache and multiprocessor memory, pipeline, superscalar, microarchitecture EPIC, the topology of the main configurations of local computer networks. A distinctive feature of the proposed system of models is the advanced animation of processes in the studied computer subsystems. An example of a superscalar processor digital model is considered, a model screen form and list of monitored parameters are presented. A data envelopment analysis technique for assessing the effectiveness of training is proposed. A linear programming problem is formulated based on the Banker-Charnes-Coope model. The graphs for evaluating the results obtained on the test group of students are given.

1. Introduction

The COVID-19 pandemic forced a reorientation to distance learning both in schools and universities. At the same time, in higher education, there is a problem of studying complex technical objects in the absence of access to laboratory equipment. Currently, the tools are being developed to provide students with remote access. The paper [1] throws light on the introduction of portable remote laboratories, which can be easily built by the students to perform digital experiments such as logic gates. This path develops practical knowledge, which often leads to a deep understanding of the theoretical concept through the act of conducting experiments and adds a personal approach to achieve practicality on the subject.

A new promising direction is the use of Digital Twins of cyber-physical systems for the construction of remote laboratories for distance learning in computer technology. A Digital Twin is a digital model of a particular physical element or a process with data connections that enable convergence between the physical and virtual states at an appropriate rate of synchronization [2]. The literature reports several examples of Digital Twin applications in the industry [3-5]. By contrast, the implementation of digital models for distance learning is more limited in number.

Some articles are devoted to the simulation of computer blocks and subsystems [6-9]. As a rule, these are software simulation models that are not combined into a general complex and do not provide control.
over the study of educational material. At the same time, such software modules can be successfully integrated into more complex systems.

We propose to consider the set of such simulation models as a digital twin of a computer. In this case, the student is able to set various modes of operation specified computer subsystem and visually observe the animation image of data processing.

The report highlights two aspects of problem-solving. Firstly, we describe a set of simulation models. It uses as components of the model previously created by the authors [10, 11]. Secondly, we propose a technique for assessing the effectiveness of distance learning based on Data Envelopment Analysis [12].

2. The system of simulation models (SSM)

The structure of the SSM is depicted in figure 1. For each type of subsystem, a set of elements and devices was selected that have a significant impact on the time characteristics. Moreover, it was decided not to represent in models of minor elements of systems, complicating the study and perception process.

Figure 1. The structure of the system of simulation models.

The described approach led to the creation of a set of simplified simulation models of computer subsystems. The structure of a computer was represented at the level of individual devices or their blocks. And the programs were simulated as sequences of machine instructions. It is well known that random factors greatly influence the operation of computer systems. In the models, random variables are used with preset probability distributions, which are set by the student.

An essential feature of the developed models is the use of animation in the user interface. It improves the perception of processes in the computer and facilitates their investigation and study.
The student can set the animation tempo in ticks and then observe data processing, dispatching, instruction execution, and the output of results in slow motion.

The set of models SSM covers four groups of the central subsystem models: I/O subsystem (input from the keyboard, output to the printer, and direct memory access); computer memory, including cache memory and multiprocessor memory; the central processor (pipeline, superscalar, microarchitecture EPIC); basic configurations of local computer network topologies.

All models have a user interface that allows students to configure settings and provide an animated output of simulated processes. The database stores the results of the conducted experiments, which makes it possible to use statistical processing.

3. Simulation of a superscalar processor
As an example, we present a simulation model of an Intel superscalar processor. Figure 2 shows the main screen form of the model.

Figure 2. The main screen form of the superscalar processor's simulation model.

The following initial data can be set in the simulation model settings window: the total number of machine instructions executed; the number of true dependent machine instructions; the percentage of a machine instruction’s different types in the program; the number of machine instructions in the loop in the program; the probability of a correct branch prediction.

It is also possible to disable the mop cache or fill it with initial values. After starting the program, an instruction mix is generated in the cache memory L1, and the sum of clock cycles in the resulting sequence is calculated. Modeling can be done in one of two modes: continuously or in processor cycles.
The student watches on the screen animation of data processing in devices, instruction queues for execution, dispatching, and reordering of instructions.

The simulation results show: a) the number of completed cycles; b) the number of incorrectly predicted branches; c) the average execution time of one machine instruction.

4. DEA method to evaluate the effectiveness of student learning using complex models

The authors have previously used the DEA methodology to analyze the performance of student interdisciplinary project teams at Samara State Technical University [13]. A similar approach will be applied to estimate the efficiency of learning using SSM.

The description of student group \( ST = \{ S_1, S_2, \ldots, S_K \} \), where \( K \) - the number of students, is to specify the set of values of input \( X \) and output \( Y \) factors for each student. A criterion for efficiency in models DEA has an integral nature. The model used is Banker-Charnes-Cooper (BCC) input-oriented model with Non-Decreasing Return to Scale (NDRS), which has the form [12]:

\[
\min_{\lambda} J
\]

under constraints

\[
\begin{align*}
-y_k + Y_k \lambda & \geq 0, \\
Jx_k - X_k \lambda & \geq 0, \\
e \lambda & = 1, \\
\lambda & \geq 0,
\end{align*}
\]

where \( J \) - integral criterion for the effectiveness, \( X \) is the matrix of inputs, \( Y \) is the matrix of outputs, \( x_k \) and \( y_k \) are the column vector of input and output parameters for the \( k \)-th student in \( X \) and \( Y \), respectively, \( e \) is a row vector with all elements unity, \( \lambda \) is a semi-positive vector and \( \lambda_i \geq 0, k = 1, K \).

It is necessary to provide \( K \) solutions of the optimization problem (1)-(2) to find unknown weights \( \lambda_k \).

5. Experimental results of evaluating the effectiveness of training

The system of simulation models SSM was used in the course "Computer Hardware (CH)." The acquired knowledge is used by students in the following disciplines in the curriculum: "Architecture of High-Performance Computing Clusters," "Computing System Design," and "Microprocessor Systems."

When assessing the student's knowledge of the course, we chose the values \( N = 3 \) for the input parameters and \( M = 3 \) for the output parameters. Input factors have the following meanings for \( k \)-th student: \( X_1k \) – a time of preparation and completion of tasks by a student using SSM, hour; \( X_2k \) – the average time for responses during input testing before laboratory work with an SSM, min; \( X_3k \) – the average rate of correct conclusions drawn from experiments performed in laboratory sessions, %.

The output indicators are:

- \( Y_1k \) – Final evaluation of progress in the study course using SSM (on a 100-point scale);
- \( Y_2k \) – Correct answer rate on input control tests with the subsequent disciplines related to CH course, studied on an SSM, %;
- \( Y_3k \) – Correct answer rate on tests on theoretical topics related to CH course, %.

Table 1 shows the parameter values for assessing the degree of knowledge acquisition for eight students in the period 2019.

| DMU | X1 (hour) | X2 (min) | X3 (%) | Y1 (point) | Y2 (%) | Y3 (%) |
|-----|-----------|----------|--------|------------|--------|--------|
|     |           |          |        |            |        |        |
The solution to the equation (1) - (2) gives the values of the weight coefficients $\lambda$, which determine the position of the subjects in the space of parameters $X$ and $Y$ relative to the efficiency frontier. The next step is to find the targets for changes in the settings of ineffective actors to achieve the efficiency frontier. Additional constraints should be considered related to the scales of these parameters:

$$0 \leq Z_k \leq 100; \quad \forall Z_k \in \{X_3, Y_1, Y_2, Y_3\}, \quad k = 1, K.$$

The graphs of the efficiency frontier in the parameter space of the students obtained using the PIM DEASoft program, are shown in figure 3 and 4.

Analysis of the graphs shows that students S1, S3, and S5 have the rating “excellent.” Students S6 and S7 are rated “unsatisfactory.” The target change in $X_3$ for student S6 to reach the efficiency boundary at the "good" level ($Y_3 = 80\%$) is 65% (figure 3). To do this, student S6 needs to increase the proportion of correct conclusions in the reports on experiments with the SSM system. From the graph in figure 4, it follows that the S7 student will receive a rating of "excellent" if he reduces the time $X_1$ of preparation and execution of tasks from 65 to 40 hours and simultaneous decreases the time $X_2$ for test answers to 20 minutes.

6. Conclusion
The system of digital models described in the article is focused on the study of basic devices and processes in a computer. However, the composition of the model is continuously changing and being upgraded to meet the novelty of computer architecture. The proposed method for assessing the success of students studying computer technologies develops in the direction of detailing didactic units. As a result, the number of controlled parameters of the educational process will be increased. The additional parameters in the DEA models will allow formulating more accurate recommendations for students to improve the quality of education [14].
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