A mathematical model for the selection of visualization system components in training complexes

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Abstract. The task of choosing the components of the visualization system for training complexes is currently being solved on the basis of expert analysis of existing equipment and technical requirements. The expert approach does not allow to automate the process of selecting components. Therefore, the urgent task is to develop a method that allows for automated decision support for the selection of visualization system components. To solve it, a mathematical model based on the use of the apparatus of the theory of sets and graphs was developed in the framework of this study. The mathematical model includes the calculation of a set of criteria to evaluate the components of the visualization system, to increase the objectivity of their choice.

1. Introduction
When designing training complexes, one of the important stages is the development of the visualization subsystem. The degree of immersion of a person in the preparation process, the speed of mastering the necessary skills and competencies depends on its quality and compliance with the requirements of the technical task. Errors made at this stage can fix incorrect knowledge in the student’s memory, which in real life can lead to an incorrect reaction to events [1].

To minimize such errors, it is necessary to objectively approach the choice of components of the visualization system. Now a similar problem is being solved by the expert method, which allows us to obtain an average, sufficient solution, but not always optimal. Its correctness depends on the knowledge and qualifications of the expert. To move to more objective approaches, it is necessary at the first stage to formalize the process of selecting components.

The analysis in the field of formalization of the classification and selection of visualization components showed an insufficient study of this issue.

In the work [2], features of the construction and optimization of the visualization system of simulators for surgeons are considered. The authors noted the need for a clear distinction between the quality of detailing of individual three-dimensional objects: excessive detailing due to limitations of existing hardware platforms will only lead to loss of productivity and will not have any positive impact on the learning process.

It should be noted the lack of sophistication of mathematical support in modern training complexes. It is usually limited to calculations of physical processes and objects in scenes, but does not affect the optimization of individual modules and subsystems. In [3], three different approaches to creating a visualization system for a car wheel replacement simulator are described. In [4], a structural diagram of the work of a training system for training paratroopers was considered. The system provides real-time training of the most important skills in a wide range of weather conditions, wind and emergency situations. The visualization system involves the use of a complex hardware system to create realistic physical loads, as well as a virtual reality helmet. In [5], a solution to the problem of the interaction of
A visualization system with a set of device simulators in an aircraft flight simulator was proposed. The mathematical apparatus presented in the work is designed to solve the problem of visual orientation during training on the simulator.

Thus, at present, the optimization of the visualization system is carried out on the basis of an expert approach by the simulator developers themselves or by customers. This assessment is carried out according to a number of criteria, among which the following can be distinguished:

- Realistic process modeling or situation is characterized by the simplicity and speed of human adaptation in the learning environment [6].
- The quality of immersion in the learning process. Analysis of how the visualization system affects the speed and involvement of a person in the learning process [7].
- Convenience and ease of use characterizes the simplicity of mastering the elements of interaction with a simulated environment created by training complexes [8].
- The presence of negative physiological sensations such as eye strain, dizziness, disorientation, and nausea [9].

However, these estimates are subjective. As part of the ongoing research on this topic, it is planned to make a transition to a set of objective criteria for assessing the visualization system and automate the process of selecting components.

In the framework of previous studies on this topic, the components of the visualization of training complexes were classified and the concept of the algorithm for their selection was formulated [10]. Based on the results obtained, it is obtained that the urgent task is to formalize the visualization system, to develop objective estimates of the components within the framework of the general mathematical model.

2. **A mathematical model for selecting components of a visualization system**

Analysis of the components of the visualization system and approaches to their assessment allowed us to formulate a mathematical model for the selection of components of the visualization system, which has the form:

\[
M(TS,P) = (HW, SW, R),
\]

where

- *TS* - technical system;
- *HW* - hardware visualization system;
- *SW* - visualization system software;
- *P* - the model of personnel activity when using a training complex;
- *R* - set of estimates of the components of the visualization system.

Hardware *HW* consists of the following subsystems:

\[
HW = (COLL, PROC, DIS, SIM),
\]

where

- *COLL* - information gathering subsystem;
- *PROC* - information processing subsystem;
- *DIS* - information display subsystem;
- *SIM* is a subsystem simulating a real environment.

Software *SW* includes:

\[
SW = (V, NET, DATA, TR),
\]

where

- *V* - set of components of visualization, including such subsets as: set of components of two-dimensional and three-dimensional visualization, set of components of the interface, set of components of lighting, set of audio components, etc.;
- *NET* - set of components of network interaction (links between elements of the visualization system);
DATA - set of components of data storage and processing;
TR - set of scenarios for staff training.
The model of personnel activity has the form:
\[ P = \{p_j\} \]
(4)
where each user corresponds to the following set of parameters:
\[ p_j \to (PS_j, PH_j, PM_j) \]
(5)
where
- \( PS_j \) - set of psychological parameters;
- \( PH_j \) - set of physiological parameters;
- \( PM_j \) - set of ordered pairs of production rules \( PR_j \) and actions \( PA_j \) carried out by the user in case the rule is met:
\[ PM_j = \{ (pr_{jk}, pa_{jk}) \}, pr_{jk} \in PR_j, pa_{jk} \in PA_j \]
(6)
There are set of rules. \( PR_j \) It is divided into two categories depending on the mode in which they are applicable:
- for normal operation: \( PR^N_j \in PR_j \);
- for emergency operation: \( PR^E_j \in PR_j \).
Each rule can be represented as: IF condition, THEN action.
Every action \( pa_{jk} \in PA_j \) makes the transition to the following state:
\[ pa_{jk}(pr_{jk}) = pr_{jm} : pa_{jk} \in PA_j ; pr_{j}, pr_{jm} \in PR_j \]
(7)
The columns are used to describe the presented model of personnel activity. \( GP_j(PR_j, PA_j) \). The graph allows you to illustrate the sequence of actions of personnel, while the production rules will correspond to the peaks \( PR_j \), and arcs set of actions \( PA_j \) to go from one rule to another. An example of such a graph is presented in figure 1.

**Figure 1.** Graph of user activity model.

Next math component models - set of evaluations of the components of the visualization system \( R \) has the form:
\[ R = (R_s, R_T, R_C, R_{TT}, R_{QT}) \]
(8)
where
- \( R_s \) - The cost of developing software for a component of a visualization system;
- \( R_T \) - Software development time for a component of a visualization system;
- \( R_C \) - The cost of operating a component of the visualization system;
- \( R_{TT} \) - Training time using a component of the visualization system;
- \( R_{QT} \) - The quality of training using a component of the visualization system.
The cost of software development is calculated by the formula:
\[ R_s = (sd_i + sa_i)k_{dev} \]
(9)
where
$sd_i$ - the cost of developing the system;

$sda_i$ - the cost of developing additional software to ensure the interconnected performance of other elements of the visualization system. Calculated by the same methods as $sd_i$;

$k_{dev}$ - the coefficient of complexity of software development for the i-th component based on expert evaluation of developers.

Software development time is calculated by the formula:

$$R_{td} = (td_i + ta_i) \cdot k_{dev},$$  \hspace{1cm} (10)

where

$t_{di}$ - system development time;

$ta_i$ - development time for additional software to ensure the interoperability of other elements of the visualization system;

$k_{dev}$ - the complexity factor of software development based on expert evaluation of developers.

The cost of operating the i-th component of the visualization system can be found by the formula:

$$R_{ci} = S_f + S_p + S_d + S_e + S_r + S_{em} + S_{oh},$$  \hspace{1cm} (11)

where

$S_f$ - costs for the purchase and delivery of the component;

$S_p$ - salary of staff;

$S_d$ - depreciation deductions;

$S_e$ - costs of energy consumption;

$S_r$ - costs of repair or restoration;

$S_{em}$ - the cost of the purchase of consumables;

$S_{oh}$ - overhead costs.

Studying time $TT_i$ using the i-th component of the ATK visualization system, based on extrapolation of empirical estimates of previous tests at training complexes:

$$R_{TT_i} = \frac{\sum_{j=1}^{nP} tt_j(v_i)}{nP},$$  \hspace{1cm} (12)

where

$tt_j$ - total training time for the user of the j-th student.

Quality training $QT_i$ using the i-th component of the ATK visualization system, depending on the success of the training tasks:

$$R_{QT_i} = \frac{\sum_{j=1}^{nP} \sum_{k=1}^{nK} vp_{jk}(v_i)}{nP \cdot nK},$$  \hspace{1cm} (13)

where

$vp_{jk}$ - the number of completed tasks when using the i-th component;

$v_{jk}$ - the full scope of tasks within the k-th competence;

$nK$ - the number of competencies analyzed.

The proposed estimates are based on the results of a system analysis of visualization components used in training complexes and training systems used in various fields of human activity, and are distinguished by their originality and scientific novelty, as previously, in aggregate, these criteria have not been considered.
3. Statement of the problem of choosing visualization tools when developing training complexes

Thus, to find the optimal solution from various points of view, we formulate the problem statement in the following form:

\[
\begin{align*}
R_S & \rightarrow \min, \\
R_T & \rightarrow \min, \\
R_C & \rightarrow \min, \\
R_{TT} & \rightarrow \max, \\
R_{QR} & \rightarrow \max,
\end{align*}
\]

when fulfilling the relations of the mathematical model (1-13) and restrictions on:

- compliance of acquired competencies \( PK \) required \( PK^* \):
  \( PK \subseteq PK^* \),

- total training time:
  \[
  \sum_{j=1}^{nk} t_{TR_j} \leq t^*_r,
  \]

- economic resources:
  \[
  R_{E} + R_{QR} \leq E^* ,
  \]

- correspondence between the selected software and hardware modules (for each module \( m_k \) belonging to the hardware and software of ATK, there is a correspondence \( cm_k \) modules included in the total set \( SW \cup HW \)):
  \[
  (\forall m_k \in SW \cup HW) \exists cm_k, cm_k (m_k) \subseteq SW \cup HW ,
  \]

where
- \( PK^* \) - a set of necessary competencies;
- \( t^*_r \) - the maximum possible training time.
- \( E^* \) - the maximum possible costs for the implementation and maintenance of ATC.

So, a multicriteria optimization problem is formulated, therefore, as a result of its solution, we obtain a certain Pareto-set of feasible solutions that satisfy the set conditions, but differ in the values of the criteria. Our task will be to choose the only solution based on the conditions of the subject area, technical specifications or other analytical considerations. Moreover, the solution that is not always the right one is optimal according to all criteria; sometimes the solution that is in the second or third places in terms of optimality shows the highest integrated efficiency.

4. Algorithm for solving the problem of selecting visualization components

Consider the algorithm for solving the problem (figure 2).

A1. Analysis of the work process. Based on the regulatory documentation, the general nature of the student’s activities at this technical facility is determined. It means a set of work performed in the normal and emergency mode.

A2. Formalization of the personnel activity model. This process consists in the formation of clear rules, algorithms for personnel actions in mathematical form.

A3. Development of technical specifications. After the final determination of the set of tasks presented to the training complex, the technical task for designing the structure of the visualization system is formed.

A4. Defining criteria and limitations. At this stage, the most important optimality criterion is determined, for example, training time, then other restriction criteria are formed on its basis, such as the cost of the visualization system, software development time, etc.

A5. Selection of components and technologies. In this block, set of components of the visualization system are determined depending on the given restrictions. The selection is based on the technical documentation of each component.
A6. The formation of the structure of the visualization system. Based on the narrowing of the set of possible components, and taking into account their limitations, a ready-made visualization system structure is formed.

Figure 2. The algorithm for solving the problem of selecting visualization components.

A7. Assessment of the structure of the visualization system. The evaluation of the finished structure is carried out according to the main criteria: the quality and time of training, the cost of buying and maintaining the finished system, the time and cost of developing software for the functioning of the training complex. The obtained estimated data allows you to finally approve the structure of the visualization system, or to refine it, returning to the stage of formation of the technical task with the subsequent adjustment of the system of restrictions and determining the optimal parameters.
5. Conclusion
In the framework of this work, a mathematical model was developed to select the components of the visualization system for training complexes. The scientific novelty of the model is the transition from an exclusively subjective expert assessment to a set of criteria allowing a comprehensive assessment of the visualization system. The mathematical model also formalizes the main components of the visualization system and the relationships between them, the activities of the simulator users, allows you to calculate the cost and time of software development for the component of the visualization system, the costs of its operation, evaluate the time and quality of training, the quality of visualization. Based on the developed mathematical model, the task of optimizing the visualization system was posed and an algorithm for its solution was proposed.

Acknowledgments
The reported study was funded by RFBR according to the research project № 19-013-00567.

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