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EVALUATION OF PROTOTYPING METHODS FOR INTERACTIVE VIRTUAL SYSTEMS BASED ON FUZZY PREFERENCE RELATION

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The object of this study is the process of determining the optimal method for prototyping interactive virtual systems using the principle of multi-criteria optimization. The paper addresses the task to design tools for evaluating prototyping methods and introduces software developed to identify the best option according to priority criteria. The optimal prototyping method was chosen based on the maximum value of the membership function with indicators of 0.3, 0.7, and 1. Thus, the best method for the given task is rapid prototyping, with a membership function value equal to 1. These results have made it possible to solve the problem by evaluating fuzzy preference relations on a set of alternatives. Additionally, a relation convolution was constructed, from which a subset of non-dominated alternatives was identified.

The key features of the proposed approach are obtaining clear quantitative evaluation parameters by processing descriptive, non-unified, and non-formalized input data. The fuzzy preference relations for the set of alternatives are explained by the analysis of the most common methods for prototyping interactive systems.

The developed information system could be used for managerial decision-making regarding the selection of optimal prototyping option from several possibilities, by comparing methods based on predefined criteria with arbitrary weighting coefficients. The result of the research is a universal system adaptable to specific user tasks. The resulting data will contribute to improving the efficiency of prototyping and, consequently, reducing costs

Keywords: interactive system, computer game, multi-criteria optimization method, fuzzy preference relation

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1. Introduction

The process of developing interactive virtual systems involves the implementation of several main stages: creation of a prototype, programming, testing, implementation. Errors made at this stage are critical as they affect all subsequent stages of system development, and their untimely detection leads to significant financial risks. In this situation, the choice of the optimal prototyping method becomes decisive; it should not be carried out on the basis of subjective opinions or preferences, which could lead to obtaining a product of inadequate quality and associated reputational losses.

Experts who can provide professional recommendations in the subject area are actively involved in the process of developing prototypes. They are surveyed by means of questionnaires or interviews [1]. An important role is played by UX/UI testing, i.e., checking user experience and user interfaces [2, 3]. Prototypes also allow for functional testing [3]. It is at the prototyping stage that the concept of digital accessibility is tested, in particular for users with special needs [4].

Prototypes are complex models of systems that reproduce all functional elements and features of interaction. They bring testing and evaluation closer to real operating conditions. This allows for an in-depth analysis of the system's effectiveness, identification of potential shortcomings, and optimization of solutions at the stages preceding implementation [5]. Given the possibility of teamwork with engineers and other developers, prototyping is a modern and effective method for designing information systems [6].

In connection with the rapid development of interactive virtual technologies and their active implementation in modern computer simulations, the pace of development should increase. This is due to significant competition and high user requirements. It is important to choose the optimal prototyping method that meets the existing requirements and challenges.

One of the urgent problems of the field of information technologies is the development of means of evaluation of prototyping methods in relation to the designed system and the creation of appropriate software. This will allow obtaining specific weight values of each alternative based on fuzzy preference relations. The results of relevant studies will help practitioners to reasonably choose a method for prototyping interactive virtual systems.

2. Literature review and problem statement

Study [7] states that prototypes are a means of building trust in the project, the main tools of communication between stakeholders and thus play a significant role in conducting negotiations, discussing concepts, and receiving feedback. The evolution of the role of prototypes in communication between interested persons is described. However, there are unresolved questions related to the comparison of the impact of different prototyping methods on communication. The reason for this may be the limited duration of the study, namely ten months. Work [8] reveals the possibilities of testing and improving the game concept at an early stage of development through the paper prototyping method. To this end, iterations were carried out, during which experts in the field of media didactics expressed their opinions. The results show that paper prototyping is a suitable method for testing game mechanics. The issue of prognostic evaluation of prototypes remained unresolved. This is due to the lack of unification of evaluation criteria obtained from different test groups. Work [9] reports a study of methods and techniques of level design of computer games. Emphasis is on prototyping using primitive forms. At the same time, the problem of formulating the main concept of this method: prototyping: "white blocks", "gray blocks" or "black blocks" remained unresolved. This is due to the lack of a systematic approach. In [10], scientific explorations of the possibilities of creating games were carried out, some early discussions about the concept of game sketching for both pedagogical and research creativity were presented. It is noted that the use of primitive forms is an important part of creating sketches that make it possible to visualize the game space. The transformation of linguistic descriptions into specific quantitative assessments, which is connected with the descriptive nature of the research, remained unresolved.

In turn, work [11] indicated that developers have limited tools for rapid prototyping, in particular with regard to augmented reality. Based on the results of the expert evaluation, three main prototyping problems were identified. A new prototyping tool has been developed. But the question of the possibility of using the developed tool to solve more problems of virtual prototypes remained unsolved. This is due to the insufficient number of interviewed experts. Work on using machine learning for rapid prototyping thanks to natural language prompts is proposed in [12]. Through interviews, it was found that rapid prototyping using machine learning accelerated the process of their development and improved communication between employees. The problem of reverse design of prompts remained unsolved, due to the need for their adjustment and evaluation of effectiveness. It is interesting to study the goals, processes, and strategies of prototyping in order to understand and use best practices [13]. It has been demonstrated that systematic and purposeful prototyping has significant value for problem solving. However, the work does not carry out a prognostic evaluation of the analyzed practices according to specific quantitative indicators, which complicates the objective analysis of the obtained results.

In work [14], a method for evaluating the effectiveness of the model was devised, which is based on a complex quality criterion, which makes it possible to choose the most suitable model by considering various classification quality criteria and assigning the appropriate significance weights. But the issues of simplifying the model remained unresolved. This is because the application of deep learning techniques to data often faces the notable problem of optimizing hyperparameters such as learning rate, batch size, and network architecture that are critical to model performance. In [15], the formation and multi-criteria evaluation of alternative options for the implementation of post-printing processes was carried out on the basis of fuzzy preference relation criteria. In [16], the level of vaccination of the population against COVID-19 was evaluated based on fuzzy parameters. However, the method for evaluating fuzzy preference relation for a set of alternatives has not previously been used in the study on prototyping features of interactive virtual systems.

Thus, the results of research on the development of prototypes of information systems are reported in [7–9]. It is shown that the stage of prototyping is of great importance and exerts considerable influence on the quality of the final result. But there are still unsolved questions about which prototyping method should be chosen in a specific situation. The reason for this is the personal preferences of developers regarding the choice of prototyping method and the difficulty of comparing methods. In [10], the method of game sketching was chosen because of the low cost of implementation, which is important for the educational field. In [11, 12], attention is focused on the need to design new tools for prototyping but there is also no evaluation of the effectiveness of the developed tools by different methods for creating prototypes. This is due to the objective difficulties of comparison and the need for considerable time. Instead, work [13] is a comparison of prototyping technologies, which distinguishes it from previous studies. However, only verbal descriptions are given, without quantification, which makes it difficult to understand the results. In [14], complex models requiring simplification were evaluated. This indicates the absence of a justified choice of the optimal method for creating prototypes. The problem can be solved by developing a theoretically based information system for evaluating alternatives, which uses the mechanism of pairwise comparison of prototyping methods according to the most priority criteria. Such criteria are duration of development, realism of the prototype, need for material and technical support, ease of iteration, identification of risks. This would allow developers to choose the best prototyping option for solving typical tasks. This effective approach is used in [15, 16], but it is not aimed at choosing the optimal method for prototyping interactive systems. All this allows us to state that it is appropriate to conduct a study aimed at comparing prototyping methods based on a fuzzy preference relation.

3. The aim and objectives of the study

The aim of our study is to evaluate the methods of prototyping interactive virtual systems based on a fuzzy preference relation and to develop the corresponding software component. This will make it possible to perform a pairwise comparison of three arbitrary prototyping methods according to priority characteristics, such as the duration of development, realism of the prototype, the need for material and technical support, ease of iteration, and identification of risks.

To achieve the goal, the following tasks were set:

– to analyze the most common prototyping methods according to key parameters;

– to form a ratio of preferences for a set of alternatives, taking into account the results of expert evaluation, to perform the calculation of membership functions in order to determine the optimal alternative;

– to design an information system for evaluating fuzzy preference relations.

4. The study materials and methods

The object of our study is the process of choosing the optimal method for prototyping interactive virtual systems based on multi-criteria optimization of fuzzy parameters. The design of interactive virtual systems is a complex, multitasking process that requires the involvement of highly qualified specialists, the use of iterative approaches and consideration of the preferences of the target audience. The basis for the creation of any innovative product is an idea formed from a set of statements and hypotheses that, for the sake of the project's success, require detailed analysis and verification. Prototyping is one of the key methods for validating assumptions, which makes it possible to confirm their correctness, viability, or reasonableness. The focus of our research is analyzing the effectiveness of prototyping methods. In this case, the essence of the idea is of secondary importance since its success is subjective and depends on many factors.

Suppose the development of an interactive virtual system is planned, which simulates the process of step-by-step production of books over a certain period of time for the purpose of further sale in a bookstore. The description of processes and events in the system is prepared using the IDEF3 model (Fig. 1).

There are a large number of prototyping methods, each with its advantages and disadvantages. It is appropriate to simplify the choice and single out the three most popular methods based on the results of expert evaluation. In the context of the stated problem, the following methods were chosen: the paper prototyping method, the gray block prototyping method, and the rapid prototyping method.

The method for paper prototyping is characterized by high speed of implementation, low cost, convenience of studying design possibilities and product concepts. Usually, such prototypes are created using sheets of paper, cardboard, pencils, markers, plastic figures, etc. During paper prototyping, the quality of the images or their details does not matter much as abstractness is the acceptable norm. The purpose of this method is to evaluate the mechanical functioning of the interactive system, as well as to receive feedback from users and observe their thoughts and emotions [8].

The "gray block" prototyping method involves using basic geometric shapes instead of detailed models. This makes it possible to focus on key aspects of game design, such as mechanics, game pacing, and player interaction. In addition, the "gray block" method facilitates rapid creation and iterative testing of levels. The main advantage is the saving of time and resources since simple forms are used instead of complex objects for initial testing. The method also makes it possible to effectively evaluate camera angles in three-dimensional spaces, which helps identify problems and improve game design at the early stages of development [9, 10].

Rapid prototyping is used to create basic samples of game ideas and mechanics. The process includes brainstorming, rapid prototyping close to the desired concept, testing with users, and making adjustments based on feedback. This makes it possible to test ideas at the early stages of development, identify shortcomings and possible improvements [11].

The choice of the optimal method for prototyping computer simulations is complicated by the presence of a significant number of objective and subjective characteristics, the priority of which is unknown, which makes quantitative evaluation impossible.

To calculate membership functions to determine the optimal alternative, it is advisable to apply the modern method for evaluating a set of alternatives $X=\{x_1, ..., x_n\}$ based on the fuzzy preference ratio H_i, the essence of which is multi-criteria optimization [14, 17]. Pairwise comparison is carried out on the segment [0; 1] and enables the representation of data in numerical form. Then, for any pair of formed alternatives (x, y), the following statements will be valid: x is not worse than y, $x \geq y$, $(x, y) \in H$; y is not worse than x, $y \geq x$, $(y, x) \in H$, x and y are not comparable, therefore $(x, y) \notin H$, $(y, x) \in H$.

In the presence of clear utility functions f_j that exist on the set X, the alternative option x with a higher score $f_j(x)$ can be considered more optimal according to the criterion j than the alternative option y with the score $f_j(y)$, which can be described by the following clear preference ratio H_j of the set X:

$$H_j = \{(x, y) : f_j(x) \geq f_j(y), x, y \in X\}. \quad (1)$$

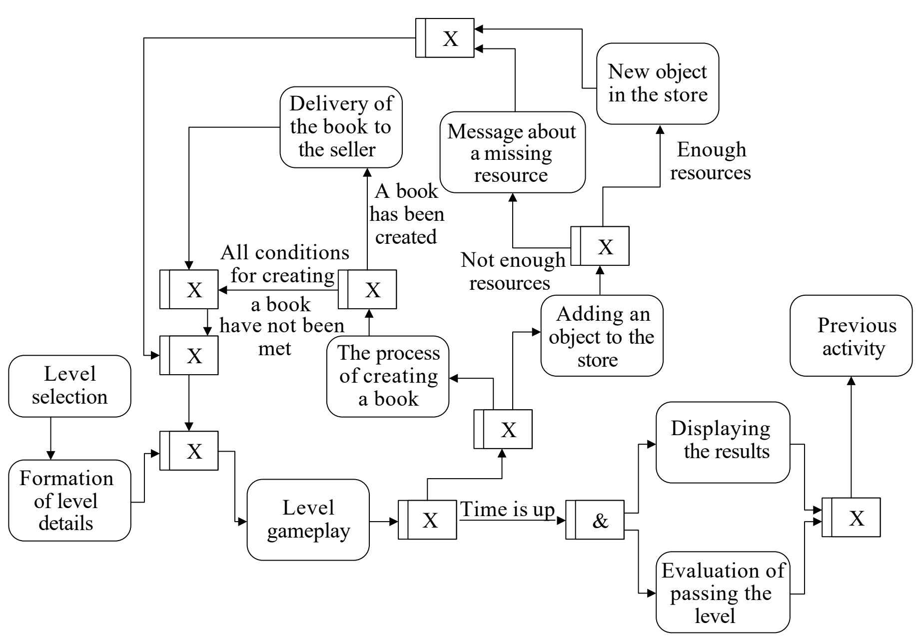


Fig. 1. Diagram describing the processes of interactive virtual systems

The next step is the selection of the Pareto-optimal alternative $x_0 \in X$, which will have the highest utility rating on the set of selected criteria and will serve as a solution to the decision-making problem regarding the fuzzy preference relation on the set of projected alternatives:

$$f_j(x_0) \geq f_j(y),\ \forall j = 1,m;\ \forall y \in X. \quad (2)$$

A convolution of the relations of sets of criteria into one scalar is formed according to the principle of intersection. To this end, we introduce the following notation: $Q_1 = \bigcap_{j=1}^{m} H_j$. The set of projected alternatives with the preference ratio Q_1 corresponds to the set with utility functions $f_j(x)$. Thus, to obtain non-dominated alternatives under a fuzzy preference relation, the set of relations $H_j(j=1, m)$ should be replaced by the intersection between them. If $\mu_j(x, y)$ is the membership function of the fuzzy preference relation H_j, we shall have the following condition:

$$\mu_j(x,y) = \begin{cases} 1, \text{if } f_j(x) \geq f_j(y), (x,y) \in H_j; \\ 0, \text{if } (x,y) \notin H. \end{cases} \quad (3)$$

Then the convolution of the criteria will take the following form:

$$\mu_{Q_1}(x,y) = \min\{\mu_1(x,y), \mu_2(x,y), ..., \mu_m(x,y)\}. \quad (4)$$

Taking into account the weighting values of the criteria and the utility function, a convolution of criteria is obtained:

$$H(x) = \min_j w_j f_j(x). \quad (5)$$

Similarly, a convolution of relations Q_2 is formed:

$$Q_2 = \sum_{j=1}^{m} w_j f_j(x), \quad (6)$$

where $\sum_{j=1}^{m} w_j = 1,\ w_j \geq 0.$

That corresponds to the membership function:

$$\mu_{Q_2}(x,y) = \sum_{j=1}^{m} w_j \mu_j(x,y). \quad (7)$$

Based on expert evaluation, three alternatives for prototyping interactive virtual systems were formed: x_1 – the first alternative (paper prototyping method); x_2 – the second alternative (the gray box prototyping method); x_3 – the third alternative (rapid prototyping method).

Alternatives were evaluated according to the following criteria: H_1 – duration of development; H_2 – realism of the prototype; H_3 – the need for material and technical support; H_4 – simplicity of iteration; H_5 – identification of risks.

5. Results of research on prototyping methods

5. 1. Analysis of prototyping methods by key parameters

To systematize the acquired knowledge, an ontological analysis was carried out: an ontology of alternatives for prototyping interactive virtual systems was built, the structure of which contributes to obtaining an optimal solution to the given task. As an example, a general ontological graph (Fig. 2) is shown, containing weighted values of criteria obtained as a result of expert decisions.

The main ontology class is prototyping methods. The classes of the second level are the methods investigated in this work, in particular the paper prototyping method, the "gray box" prototyping method, and the rapid prototyping method. Factors influencing the quality of prototyping are, accordingly, third-level classes.

The duration of designing a prototype of interactive virtual systems was analyzed and the time spent on its construction was compared, taking into account each iteration separately. The number of game objects used during the development of the prototype, as well as the need for knowledge of game engines and programming languages, were taken into account to estimate resource costs. In the context of risk identification, it was assessed which risks were identified by each of the prototypes for further development. When evaluating the real state of the prototype, it was determined how accurately the prototypes reflected the real game, the presence of mechanics and elements that could be used in future developments have been checked. The ease of iterations, feedback capabilities, and the complexity of updating interactive systems were assessed.

Fig. 3 shows the results of implementing prototypes using different methods.

To compare methods for prototyping an interactive virtual system, the time spent on development was chosen. The total time spent T was calculated:

$$T = \sum_{k=1}^{n} t^k, \quad (8)$$

where t is the time required to design an iteration of the prototype, n is the number of iterations (in this case, $n=3$).

Time characteristics were found for each prototyping method: paper prototyping $T_p=5$; prototyping with "gray boxes" $T_b=14$; rapid prototyping $T_s=10$.

Visualization of the time spent on the design of the system prototype and for each iteration is shown in Fig. 4. The length of time spent on developing the first iteration of the prototype is given separately.

The results show that paper prototyping is the fastest of the three methods. This method is quite abstract and requires no coding to function. The total time to develop all iterations of the paper prototype was also short, which helped get a lot of ideas and feedback from players in a short period of time. The rapid prototyping method is more interactive than greybox, and in the case of greybox, the focus is on game mechanics and their testing, and thus on their time-consuming programming.

A derivative of the prototyping time criterion is the simplicity of iterations, where the time spent on prototyping is also used. To determine the criterion of ease of iteration and accuracy, Fig. 4 shows the time spent on each iteration: $t_{p_1} = 3$ hour; $t_{p_2} = 1$ hour; $t_{p_3} = 1$ hour; $t_{b_1} = 6$ hour; $t_{b_2} = 5$ hour; $t_{b_3} = 3$ hour; $t_{s_1} = 5$ hour; $t_{s_2} = 2$ hour; $t_{s_3} = 3$ hour.

Time is not sufficient to determine the best method for developing iterations because time does not take into account new or changed mechanics and game elements added in a new iteration. It is logical to assume that with more game elements, the time to develop iterations increases.

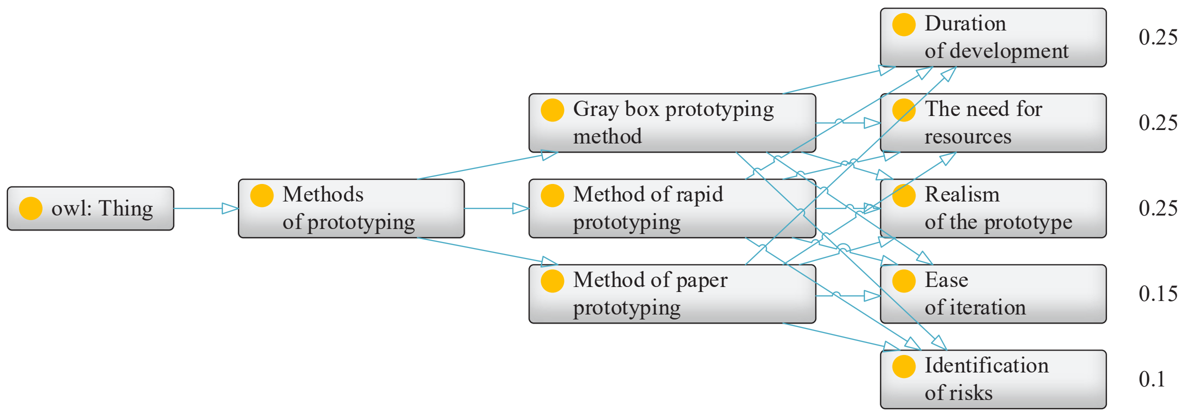


Fig. 2. General ontological graph of prototyping alternatives in interactive virtual systems

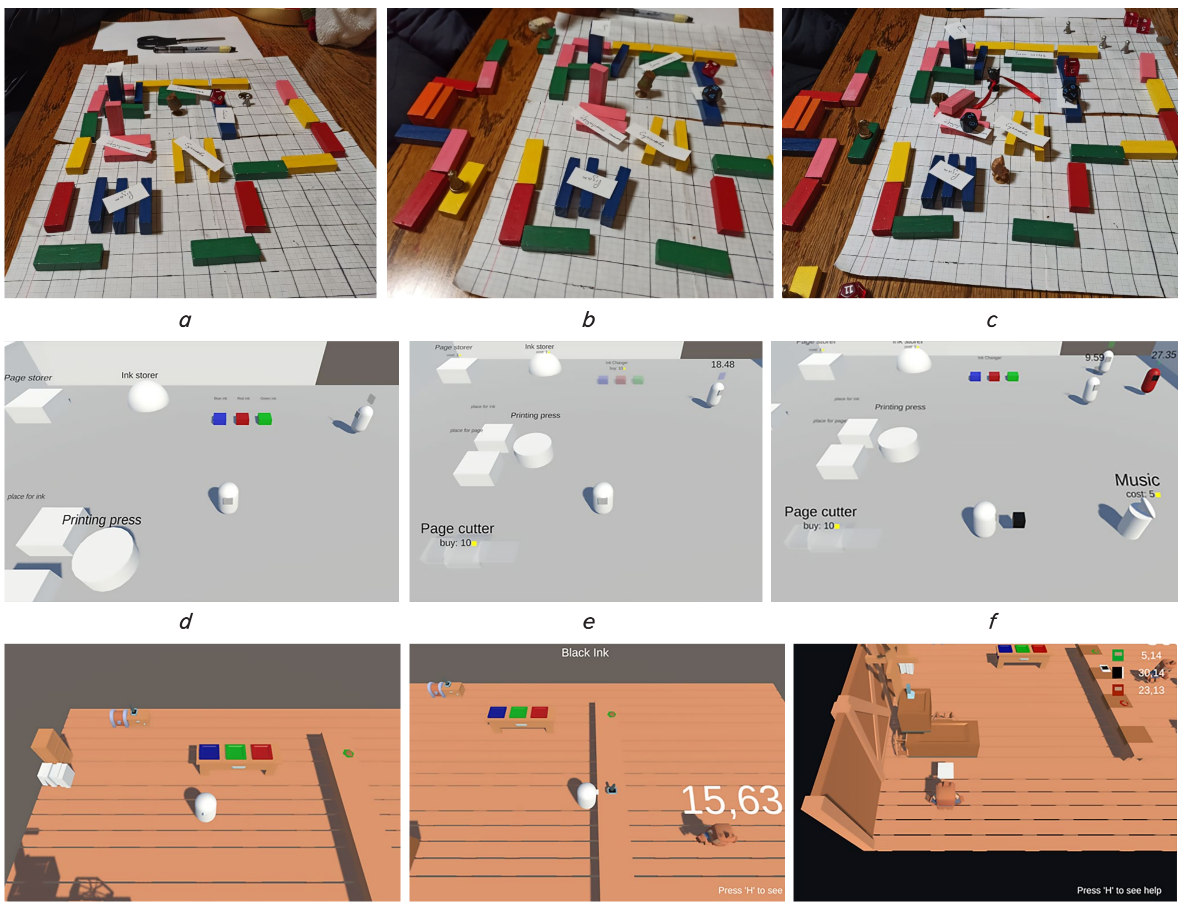


Fig. 3. Results of implementing the prototyping by using different methods: *a* – the first iteration using the paper prototyping method; *b* – the second iteration using the paper prototyping method; *c* – the third iteration using the paper prototyping method; *d* – the first iteration using the "gray box" prototyping method; *e* – the second iteration according to the "gray box" prototyping method; *f* – the third iteration using the "gray box" prototyping method; *g* – the first iteration using the rapid prototyping method; *h* – the second iteration according to the method for rapid prototyping; *i* – the third iteration using the rapid prototyping method

To define the best method, we determine the average value of the number of game elements created in one hour of work on the prototype:

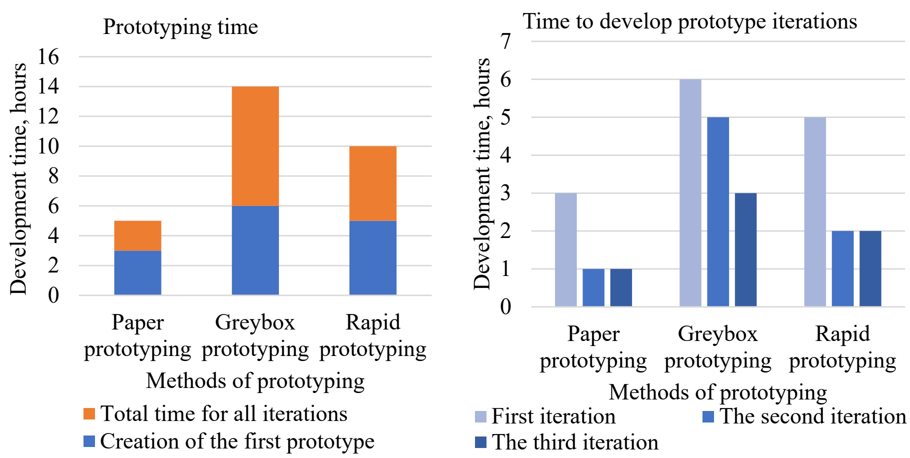
$$M=\sum_{k=1}^{n} m^k, \qquad (9)$$

where m is the value of the game mechanics created in one hour of development of a certain iteration of the prototype. The value m is determined from the following formula:

$$m=\frac{h}{t}, \qquad (10)$$

where h is the total number of new or changed elements of the iteration, t is the time spent on the development of the prototype iteration.

Table 1 lists the changed or added mechanics and elements of the interactive system for each of the prototyping iterations, as well as their number.



a *b*

Fig. 4. Visualization of the time spent on the design of system prototypes and iterations of prototypes: *a* – analysis of the time spent on the design of prototypes; *b* – analysis of the time spent on the development of iterations of prototypes

Table 1

A list of game elements in the iterations of an interactive system

Iteration designation	Iteration ID	New/changed Items	Total number of elements
h_{p_1}	The first iteration – a paper prototype	Player role, buyers, shop tools, book creation details, different book colors, different order sizes, order creation time, game level	8
h_{p_2}	The second iteration – a paper prototype	Supply building, day and night cycle, enemy patrols, item spawn time, item spawn tracking	5
h_{p_3}	The third iteration – a paper prototype	Co-op, breaking workbenches, improving tools, starting the game	4
h_{b_1}	The first iteration – a greybox prototype	Player, camera movement, placing objects on planes, creating a book, details of books, description of tools, arrival of a buyer with an order	7
h_{b_2}	The second iteration – a greybox prototype	Money, order time UI, buy tools, new tools, order complications over time	5
h_{b_3}	The third iteration – a greybox prototype	A new tool, a mechanism for extending/reducing customer waiting time, a new type of buyer	3
h_{s_1}	The first iteration – a rapid prototype	Player, camera movement, placing objects on planes, creating a book, details of books, types of orders, arrival of a buyer with an order, placing an order	8
h_{s_2}	The second iteration – a rapid prototype	UI help, buyer timer, new buyers, UI item name, end game	5
h_{s_3}	The third iteration – a rapid prototype	Music and sound effects, character animation, customer arrival time, UI timer indicator, table changes, shop interior change	6

The m value of each of the prototyping methods was found: $m_{p_1}\approx 2.67$, $m_{p_2}=5$, $m_{p_3}=4$; $m_{b_1}\approx 1.17$, $m_{b_2}=1$, $m_{b_3}=1$, $m_{s_1}=1.6$, $m_{s_2}=2.5$, $m_{s_3}=2$. Average values of the number of game elements created in one hour M for each of the prototyping methods were obtained: M_p=3.89; M_b=1.06; M_s=2.03.

The most convenient method for iteration is the paper prototyping method. It is quite abstract, with a simplified process of adding or removing details. The second simplest iteration is the method for rapid prototyping, built on the basis of an iterative approach. The gray box prototyping method is the most difficult to perform iterations because in this method, detailed creation of scripts for mechanics and adding new mechanics require additional time.

To compare the methods in view of the spent resources, we shall determine the number of tools used for creating prototypes: Parer prototyping – notebook, blocks of the game "Jenga", chess, coins (total number – 4); Greybox prototyping – Unity engine, C# language (total number – 2); Rapid prototyping – Unity engine, C# language, texture materials, 3D objects, music, effects, animation (7 in total).

Finally, the least demanding in terms of resources is the "gray boxes" method, which requires knowledge of one of the game engines and a programming language. Despite the fact that certain resources are required for a paper prototype, one can do with paper and a pen because the method itself is quite abstract. The most "demanding" in terms of resources is the method for rapid prototyping but at the same time it is the most suitable for the analyzed game product.

To compare the risk detection criteria r, we determine which of the methods was able to detect the largest number of risks. It is also necessary to take into account the importance of the criterion of criticality of this risk.

Risks are derived from player feedback. The expert assessment determined the criticality of each of the risks, the values of which are responsible for the following:

– q=1: low risk criticality;
– q=3: average risk criticality;
– q=5: high risk criticality;
– q=7: very high risk criticality.
– q=2, 4, 6: compromise intermediate values.

The following formula was used to find the criticality rating R of each of the methods:

$$R=\sum\nolimits_{k=1}^{j} q^k, \quad (11)$$

where j is the number of method risks found, q is the criticality of each of the risks found.

The average value of the level of criticality of risks $\overline{R}$ was obtained from the following formula:

$$\overline{R}=\frac{R}{j}. \tag{12}$$

The total number of risks found for each of the methods was obtained: j_p=10; j_b=17; j_s=15. The criticality assessment R of each of the methods was determined: R_p=41; R_b=90; R_s=64. The average value of the level of criticality of the risks found was calculated: $\overline{R}$: $\overline{R}_p=4.1$; $\overline{R}_b\approx 5.3$; $\overline{R}_s\approx 4.2$.

The gray box prototyping method best detects risks. The number of risks found j_b=17 is the largest at the highest criticality. The second place is occupied by the method for rapid prototyping. Although the number of risks found is close to the gray box prototyping method, the average risk criticality is much lower. The paper prototyping method is the weakest in terms of abstractness.

The essence of expert evaluations on a 5-point scale is given, which will determine the level of approximation to the final product of prototypes obtained by various methods: 0 – not implemented in the prototype; 1 – abstract compared to a real product; 2 – simplified compared to the real product; 3 – approximately close to the real product; 4 – close to the real product; 5 – similar to the real product.

Table 2 gives the main elements of the system and their expert evaluations in relation to each of the prototyping methods.

Table 2

List of system formation criteria

Name of the interactive system element	Paper prototyping method	Gray box prototyping method	Rapid prototyping method
Game mechanics	3	4	4
Game interface (UI)	0	2	3
Visuals of the game	1	1	3
Audio elements	0	0	4
Game goal	2	2	2
In-game resources	1	3	2

The average value of closeness to real $\overline{A}$ is determined from the following formula:

$$\overline{A}=\frac{\sum_{k=1}^{n}c^k}{n}, \tag{13}$$

where c is the evaluation of the game element, n is the number of elements: $\overline{A}_p\approx 1.17$; $\overline{A}_b=2$. $\overline{A}_s=3$.

The closest to the real product is the prototype obtained by the method of rapid prototyping with the average value of the evaluation level "3", which means an approximate approximation to the real product. This is followed by the gray box prototyping method, in which the prototype is simplified compared to the actual product due to the absence of music and graphic objects. In the last place in terms of product realism is the paper prototyping method, the result of which is abstract compared to the final product.

5. 2. Formation of preference relations and calculation of membership functions

According to the above results and experts' assessments, let the defined criteria determine the following ratio of preferences for a set of alternatives:

$$\begin{aligned}&H_1: x_1<x_2,\, x_1<x_3,\, x_2>x_3;\\&H_2: x_1<x_2,\, x_1<x_3,\, x_2<x_3;\\&H_3: x_1>x_2,\, x_1<x_3,\, x_2<x_3;\\&H_4: x_1>x_2,\, x_1>x_3,\, x_2<x_3;\\&H_5: x_1<x_2,\, x_1<x_3,\, x_2>x_3.\end{aligned} \tag{14}$$

It is necessary to find the best compromise solution according to the set of criteria, using the convolution Q_1, Q_2. At the same time, the weights of the criteria are taken for Q_2:

$$w_1=0.25;\, w_2=0.25;\, w_3=0.25;\, w_4=0.15;\, w_5=0.1.$$

Solving the task.

The relationship matrix H_1 is constructed. We consider all relations to be transitive. We used the ratio:

$$\mu_H(x,y)=\begin{cases}1, \text{ if } x_i\geq x_j, \text{ or } x_i\approx x_j;\\0, \text{ if } x_i<x_j.\end{cases} \tag{15}$$

The relation matrices were constructed – H_1, H_2, H_3, H_4, H_5 (Table 3).

A convolution of relations has been built $Q_1=H_1\cap H_2\cap \cap H_3\cap H_4\cap H_5$ (Table 4).

Table 3

Relation matrices

$\mu_{H_j}(x_i,x_j)$	x_i/x_j	x_1	x_2	x_3
$\mu_{H_1}(x_i,x_j)$	x_1	1	0	0
	x_2	1	1	1
	x_3	1	0	1
$\mu_{H_2}(x_i,x_j)$	x_1	1	0	0
	x_2	1	1	0
	x_3	1	1	1
$\mu_{H_3}(x_i,x_j)$	x_1	1	1	0
	x_2	0	1	0
	x_3	1	1	1
$\mu_{H_4}(x_i,x_j)$	x_1	1	1	1
	x_2	0	1	0
	x_3	0	1	1
$\mu_{H_5}(x_i,x_j)$	x_1	1	0	0
	x_2	1	1	1
	x_3	1	0	1

Table 4

Convolution of relations

	x_i/x_j	x_1	x_2	x_3
$\mu_{Q_1}(x_i,x_j)$	x_1	1	0	0
	x_2	0	1	0
	x_3	0	0	1

A subset of non-dominant alternatives was found:

$$\mu_{Q_1}^{nd}(x)=1-\sup\{\mu_{Q_1}(y,x)-\mu_{Q_1}(x,y)\}; \tag{16}$$

$$\mu_{Q_1}^{nd}(x_1)=1-\sup(0-0;0-0)=1;$$

$$\mu_{Q_1}^{nd}(x_2)=1-\sup(0-0;0-0)=1;$$

$$\mu_{Q_1}^{nd}(x_3)=1-\sup(0-0;0-0)=1.$$

Thus $\mu_{Q_1}^{nd}(x)=[1;1;1]$.

A fuzzy preference relation Q_2 (adaptive convolution of relations H_1) was constructed. Its membership function is given in Table 5.

Table 5

Membership function

	x_i/x_j	x_1	x_2	x_3
$\mu_{Q_2}(x_i,x_j)$	x_1	1	0.4	0.15
	x_2	0.6	1	0.35
	x_3	0.85	0.65	1

A subset of non-dominated alternatives for the relation Q_2 was found:

$$\mu_{Q_2}^{nd}(x)=1-\sup\left\{\sum_{j=1}^{m}\mu_{Q_2}(y,x)-\mu_{Q_2}(x,y)\right\}; \quad (17)$$

$$\mu_{Q_2}^{nd}(x_1)=1-\sup(0.6-0.4;0.85-0.15)=0.3;$$

$$\mu_{Q_2}^{nd}(x_2)=1-\sup(0.4-0.6;0.65-0.35)=0.7;$$

$$\mu_{Q_2}^{nd}(x_3)=1-\sup(0.15-0.85;0.35-0.65)=1.$$

Thus $\mu_{Q_2}^{nd}(x)=[0.3;0.7;1]$.

The intersection of the sets Q_1^{nd}, Q_2^{nd} was found and we calculate the membership function of the resulting subset $Q_{nd}=Q_1^{nd}\cap Q_2^{nd}$. Its membership function is equal to:

$$\mu_{nd}(x)=\min\left\{\mu_{Q_1}^{nd}(x),\mu_{Q_2}^{nd}(x)\right\}; \quad (18)$$

$$\mu_{Q}^{nd}(x)=[0.3;0.7;1].$$

Therefore, the best choice in the considered case is the x_3 alternative.

The membership function of the convolution Q shows that the optimal alternative with the above ratios of utility preference of the factors is the option x_3, the membership function of which has the maximum value [16, 17]. The obtained data confirm the reliability of our research results.

5. 3. Information system for evaluating fuzzy preference relations

Description of the algorithm for determining the optimal alternative based on a fuzzy preference relation for choosing a method for prototyping an interactive virtual system:

1. The quality of the researched technological process was determined by evaluating the fuzzy preference relation H_1 on the set of alternatives $X=\{x_1, x_2, x_3\}$: $H_1, ..., H_5$.

2. Matrices of relations for factors H_1, H_2, H_3, H_4 and H_5 were formed. We shall use two types of numerical visualizers: 0 and 1, where 0 is no preference.

3. A convolution of relations $Q_1=\bigcap_{j=1}^{5}H_j$. was constructed.

4. According to the convolution of relations Q_1, the subset of non-dominated alternatives will take the following form:

$$\mu_{Q_1}^{nd}(x)=1-\sup_{y\in X}\left\{\sum_{j=1}^{5}\mu_{Q_1}(y,x)-\mu_{Q_1}(x,y)\right\}. \quad (19)$$

5. A fuzzy preference relation was established – $Q_2, j=1,5$:

$$Q_2=\sum_{j=1}^{5}w_j h_j(x). \quad (20)$$

6. An additive convolution of relations with membership functions was defined:

$$\mu_{Q_2}(x,y)=\sum_{j=1}^{5}w_j\mu_j(x,y),\ \sum_{j=1}^{4}w_j=1,\ w_j\geq 0. \quad (21)$$

7. A set of non-dominant alternatives for Q_2 was built:

$$\mu_{Q_2}^{nd}(x)=1-\sup_{y\in X}\left\{\sum_{j=1}^{5}\mu_{Q_2}(y,x)-\mu_{Q_2}(x,y)\right\}. \quad (22)$$

8. To define the Pareto-optimal alternative, the intersection of the sets Q_1^{nd} and Q_2^{nd} was performed and the membership function of the common set was determined:

$$Q_{nd}=Q_1^{nd}\cap Q_2^{nd}; \quad (23)$$

$$\mu_{nd}(x)=\min\left\{\mu_{Q_1}^{nd}(x),\mu_{Q_2}^{nd}(x)\right\}. \quad (24)$$

The most effective alternative is selected based on the maximum numerical value of the membership function $\mu_Q^{nd}(x_i)$.

The PrototypeAssessment information system has been designed, the interface of which is shown in Fig. 5.

The program makes it possible to form fuzzy preference relations among three arbitrary methods for prototyping interactive systems according to the following factors: duration of development, realism of the prototype, need for material and technical support, ease of iteration, identification of risks. In addition, it is possible to set weight values of factors, that is, to form their priority level for a specific case. The result of program performance is the maximum value of the membership function, that is, determining the optimal alternative.

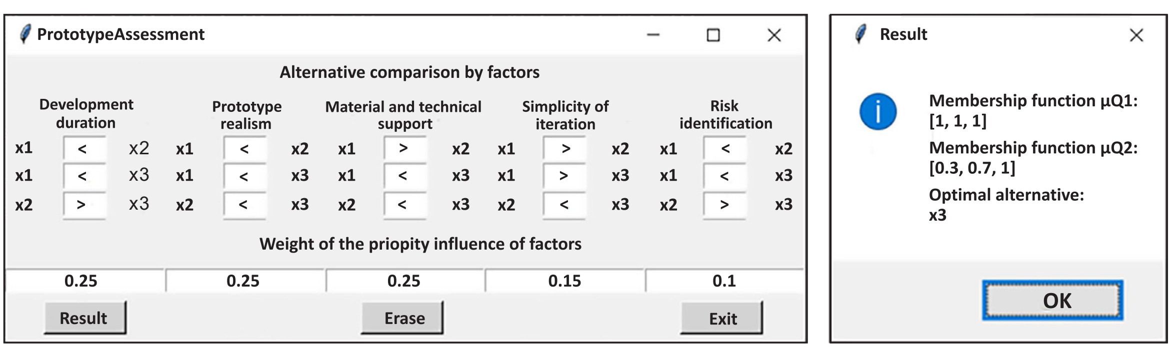


Fig. 5. PrototypeAssessment program interface

6. Discussion of results of investigating prototyping methods

The main focus of the research is on the use of prototyping methods for interactive virtual systems and the determination of the optimal prototype by the method of multi-criteria optimization of key quality criteria. This has made it possible to represent and compare alternatives numerically through pairwise comparison of options. The conceptual provisions of decision-making theory [18–20] became the basis for identifying patterns and principles of prototyping in the design of an information system.

The development of prototypes (Fig. 3) in relation to a specific task (Fig. 1) has made it possible to conduct a thorough analysis of methods for paper prototyping, "gray block" prototyping, and rapid prototyping. The study was conducted on key factors based on player feedback and expert evaluations and enabled a pairwise comparison of alternatives based on a fuzzy preference relation. In particular, the fuzzy preference relations for the "development duration" factor are due to the obtained results in expression (8). Relationships according to the factor "ease of iterations" are determined by the number of created game elements in one hour (9), (10). The number of used means for creating prototypes was obtained experimentally. A comparison of the effectiveness of risk detection is obtained from (12), the realism of prototypes is obtained from (13). The result of the multi-criteria optimization based on the fuzzy preference relation is the membership function (18), the maximum value of which indicates the optimal prototyping method for the given conditions. Our procedure has made it possible to develop an algorithm for the information system for evaluating prototyping methods, the description of which is reported in the study. Thus, as a result of the development of the algorithm for evaluating methods of prototyping interactive systems, appropriate software was created (Fig. 5), which would make it possible to reduce management risks regarding the choice of the optimal method for building prototypes among a set of possible options.

In contrast to [13], in which a classification of the advantages of prototyping technologies is given, but their quantitative assessment is not presented, our study presents a quantitative assessment. A clear information justification for choosing the optimal method for creating prototypes was formed based on a pairwise comparison of alternatives according to the most priority criteria. Such criteria are the duration of development, the realism of the prototype, the need for material and technical support, ease of iteration, and identification of risks. The designed information system could allow for quick and effective decision-making under conditions of uncertainty, indicating the relationship between factors and their priority.

Thus, the practical results of the research could be used to make decisions regarding the choice of the method for prototyping interactive virtual systems.

This work expands the previous research aimed at:

– prognostic evaluation of the quality of tactile products according to the theory of fuzzy sets [21];

– modeling alternative web design options using methods based on linear collapse of criteria and fuzzy preference relation [17].

The limitations of this study are that users will not be able to change or add to the list of factors, which may not cover all individual needs, because it is not exhaustive. In addition, only three prototyping methods can be compared. That is, the number of comparative methods is limited.

The disadvantage of our study is that once the key members of the team working on the prototype change, the results of the method comparison may not be relevant. This is related to the team's professional skills, experience with a certain prototyping method. Thus, the study will need to be repeated, testing the effectiveness of the methods for an updated collective of designers.

A possible area of our future research is the use of neural network technologies to optimize the process of evaluating the quality of an interactive system prototype. It could also pave the way for a comparative analysis of different types of deep learning models for linguistic variable data processing, which would make it possible to obtain a predicted integrated quality score.

7. Conclusions

1. Methods of paper prototyping, gray box prototyping, and rapid prototyping of interactive systems have been compared. This enabled the further formation of pairwise preferences for multiple alternatives, which is the main advantage compared to other methods. An analysis of time spent on creating prototypes was carried out. Paper prototyping was found to be the fastest of the three methods due to the lack of coding required. Time spent on all iterations was only 5 hours. The time taken for each iteration and the average number of game elements created in one hour have been shown. The indicated indicators demonstrate that the paper prototyping method is also the most convenient for iteration while the "gray box" prototyping method is the most difficult because the detailed creation of scripts and the addition of new mechanics require additional time. To compare the methods in view of the spent resources, the number of used means for creating prototypes was determined. The "gray box" method requires the least volume of resources (2 elements), the largest – rapid prototyping (7 elements). Estimates of criticality and average values of the level of criticality of isolated risks were calculated. The gray box prototyping method detects risks best because the number of found risks $j_b=17$ is the largest at the highest criticality $R_b=90$. Much worse risk detection is observed with paper prototyping: $j_p=10$, $R_p=41$. The realism of prototypes was determined on the basis of expert evaluations on a 5-point scale. The average value of closeness to the real product is the highest for the prototype obtained by the rapid prototyping method, the lowest – for the paper prototyping method, the result of which is abstract compared to the final product. Our results are explained by comparing the indicators of the prototypes according to the feedback of the players and the evaluations of experts.

2. The optimal method for prototyping an interactive system based on multi-criteria optimization has been defined, in which the most priority factors influencing the quality of the prototype are the criteria. The advantage of this method is the possibility of unifying disparate data and verbal descriptions using a fuzzy preference relation and obtaining a specific numerical indicator of the value of the membership function, which is calculated based on the intersection of subsets of non-dominated alternatives. To this end, matrices of relations by factors and a convolution of the indicated relations were constructed. A subset of non-dominated alterna-

tives was formed by convolution of relations $\mu_{Q_1}^{nd}(x)=[1;1;1]$. A fuzzy preference relation and each element of the matrix of relations with respect to the analyzed alternatives were determined. In this way, we obtained $\mu_{Q_2}^{nd}(x)=[0.3;0.7;1]$, which is the resulting subset. According to the membership function of the convolution Q, the optimal alternative with the given ratios of the utility preference of the factors is the option x_3 with the maximum value of the membership function $\mu_Q^{nd}(x_3)=1$. That is, with the weights of the factors set by the experts, the method of creating rapid prototypes is optimal for prototyping an interactive system.

3. The PrototypeAssessment information system has been designed, which allows evaluation of interactive systems prototyping methods according to dominant factors: duration of development, realism of the prototype, need for material and technical support, ease of iteration, identification of risks. The uniqueness of the system is the possibility of comparing any methods for creating prototypes according to the specified parameters. Also, the user is given the opportunity to independently choose the importance of each factor, which is due to the variety of possible tasks and project features. Our study provides a description of the algorithm of the system, which concisely demonstrates the principles of calculating the best alternative by the method based on the fuzzy preference relation. The results obtained by the program are identical to the performed calculation, which indicates the adequacy of the problem solution: $\mu_{Q_1}^{nd}(x)=[1;1;1]$, $\mu_{Q_2}^{nd}(x)=[0.3;0.7;1]$, the optimal alternative is x_3.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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