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PROCESS OF DECISION-MAKING IN DEVELOPMENT OF COMPLEX TECHNICAL SYSTEMS AND THE TASK OF CHOICE OF ALTERNATIVES

Developing highly competitive products involves making well-grounded and correct decisions which can be ensured by a systemic approach to the creation of new products and advanced decision-making methods. One of the primary concepts of system analysis is the concept of decision-making. The paper considers the primary lifecycle stages of a complex engineering system (CES), the statement of the decision-making problem in respect to CES development and conditions of selection of solution methods as part of alternative solutions analysis. The authors demonstrate the significance of the decision-making process at various stages. From the standpoint of state-of-the-art concepts, the paper provides a detailed description of the decision-making procedure proper that involves seven stages – from the purpose of problem solution to its implementation.

Keywords: *complex engineering system, multilevel complex engineering systems, system analysis, lifecycle, lifecycle stage, decision-making process, decision-maker, alternative, efficiency indicators and criteria.*

Introduction

The decision-making theory provides the recipe for the choice of human behavior in various situations. As the society and information technology develop, the conditions in which people find themselves get more complex as well.

The rational decision-making theory is to answer two questions:

1) What information is relevant to this choice;

2) How to compare them in order to come to the correct conclusion.

The main property of a rational decision is its optimality, i.e. other conditions being equal, the chosen alternative must have the highest rating.

This simple principle of maximized gain and minimized loss appears to be the most reasonable in simple situations [1]. In case of technical objects (engineering systems) our incorrect actions can cause them to not perform their main functions, as well as financial and time loss. In the age of scientific and technical progress, the advent of the new era of innovation based upon new and, first of all, information technologies, the choice of the correct and scientifically grounded decision becomes more and more relevant.

Both in Russia and abroad, a whole system of product quality assurance has been developed. A new science, qualimetry, has emerged that deals with the measurement of the quality of various objects [2, 3].

This science is based on state-of-the-art methods and models of quality and performance evaluation of developed products and is successfully developing as evidenced by a multitude of articles in periodical publications, as well as a number of educational books and monographs [4-8].

In 1990s, with regards to special-purpose products, a method of performance evaluation of weapons and military equipment (WME) using mathematical methods of decision-making and expert evaluation theory [9] was suggested and later tested and used for the purpose of WME evaluation [10-12]. This computer-assisted method was widely discussed in the defense systems engineering community due to its simplicity, affordability, dependability and quick delivery of results [13].

This article analyzes the distinctive features and specifies the primary concepts of system analysis, concept of goal setting for decision-making and choice in the development of complex engineering systems, as well as the main stages of decision-making.

1. Distinctive features of state-of-the-art engineering systems

Most state-of-the-art engineering systems are complex, therefore we should focus the discussion on CESs that can be defines as follows: «System is an entity internally organized one the basis of a certain principle, in which all the elements are so closely related that they act as an integral whole towards the environment and other systems» [14]. No formal and strict definition of a complex or large system exists yet. Let us note the primary system properties a CES must have [15, 16]. Those are the integrity

Table 1. CES lifecycle stages, goal and alternatives at stages as per GOST ISO 15288- 2002

<table>
<tr><th>Lifecycle stages</th><th>Goal</th><th>Alternative solutions</th></tr>
<tr><td>1. Design</td><td>– Customer requirement definition
– Concept study
– Development of proposals for viable decisions</td><td rowspan="2">– Next stage execution
– Resumption of stage
– Transition back to the previous stage
– Project execution delay
– Project interruption</td></tr>
<tr><td>2. Development</td><td>– System requirements specification
– Design of draft decision
– System construction
– System verification and validation</td></tr>
<tr><td>3. Production</td><td>– System production
– Inspection and testing</td><td rowspan="2"></td></tr>
<tr><td>4. Operation</td><td>– Use of the system for satisfaction of customer requirements</td></tr>
<tr><td>5. Maintenance</td><td>– Maintenance of system capabilities</td><td rowspan="3"></td></tr>
<tr><td>6. Decommissioning</td><td>– Storage, archiving and decommissioning</td></tr>
<tr><td>7. Disposal</td><td></td></tr>
</table>

Notes.

Verification *is the evidence-based confirmation of the fact that the specified requirements have been met. In the context of system lifecycle, the verification is a package of measures aimed at comparing the results of a system lifecycle with the respective required values. The lifecycle results (without limitations) are the specified requirements, project description and system itself.*

Validation *is the evidence-based confirmation of the fact that the requirements specified for a certain use or application have been met. In the context of system lifecycle, validation is a package of measures that guarantee and ensure that a system is capable of performing the specified functions in accordance with the specified goals and purposes in specific operational conditions.*

and modularity of an object, presence of more or less stable connections (relations) among the system elements, though not any connections are considered defining from the system point of view, but only significant ones that define the integrative properties of systems, presence of integrative properties intrinsic to the system as a whole, but not to individual elements, and organization of evolutionary systems that manifests itself in the structural features of the system, its complexity, ability to preserve itself and develop.

The system analysis recommends beginning the decision-making process with the identification and clear definition of the ultimate goals, considering the problem as an integral system and identifying all consequences and connections of each specific solution, coordinating subsystems goals with the common system goal, identifying and analyzing possible ways of reaching the goal and choosing the most efficient ones.

Decisions have to be taken at all stages of CES lifecycle. According to the national Russian standard «Information Technology. System Engineering. System life cycle processes ISO/IEC 15288:2002», there are six lifecycle stages (table 1) [17]: design; development; manufacture; application; application support management; decommissioning and disposal.

The stages can be used to design structures that help use lifecycle processes in modeling the lifecycle itself. The scale and accuracy of process application within the described stages and subject to their duration depend on the changing engineering and business requirements of the CES (project) that define and use the lifecycle. An example of information support (IS) of CES in the area of WME is shown in fig. 1[18].

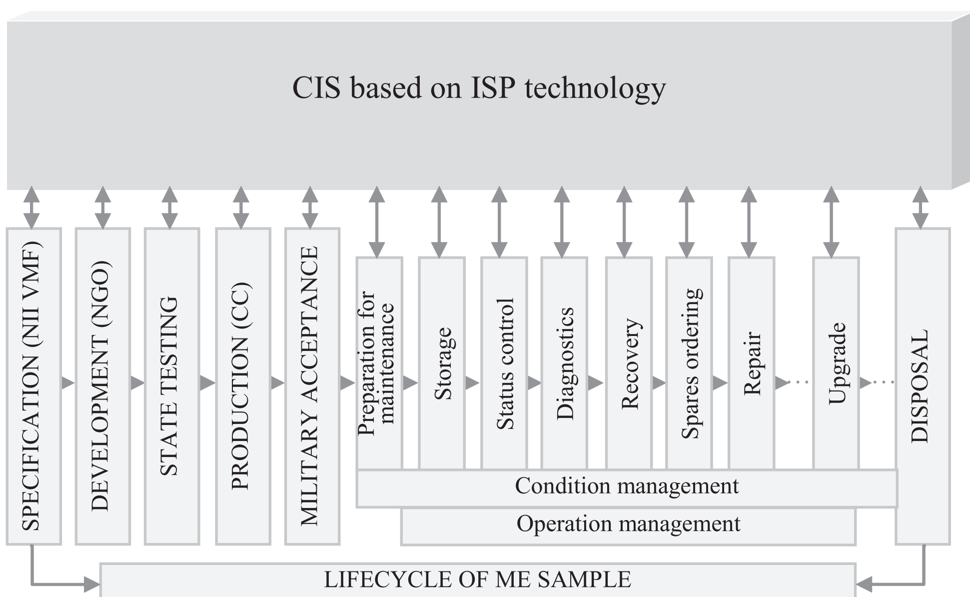


Fig. 1. Implementation of IS technologies at WME lifecycle stages: CIS – common information space, ISP – information support of products, ME – military equipment

2. Concept of goal setting for decision-making and choice

The choice strategy can be based on the suggested suites of methods, developed models and algorithms. In the process of development, the decision-maker has to solve decision-making tasks at the stages of strategical forecasting, planning, resources distribution, generation (synthesis) of alternatives, etc. The solution of such tasks comes down to choosing one or more best alternatives from defined sets [19]. In order to make such choice, it is required to clearly define the goal, tasks and criteria (a whole set of quality indicators), that will be used in evaluations for a certain set of alternatives.

There is abundance of various methods of specifying the task for making substantiated decisions while choosing among CES objects [20]. We will consider one of the alternative methods as applied to criteria extremalization choice.

Let x be a solution whose alternatives are defined within the allowable set X. The quality of decisions made by the decision-maker is defined by n scalar criteria R_j, $j = 1, 2,...,n$, the evaluations based on which form the efficiency vector $r = r_1,\ldots,r_n$. This particular vector is connected to the alternative x by the function $F: X \to R$ that can be defined analytically, statistically or heuristically. It is required to find a set of best alternatives Y that meets the following requirements:

$$Y_x = \{\forall\, y \in \mid \exists\, X \in X : r\,(x) \succ r\,(y)\}.$$

In this case it is assumed that the criterial evaluation $r\,(x)$ for the alternative x depends only on this alternative and does not depend at all on any other alternatives in the set X.

With respect to CES development, the procedure of control task definition in decision-making consists of three stages: the task of analysis and theoretical research for task definition, development of a concept, suite of methods and mathematical models, organization of the testing process and implementation capabilities. The content of the stages is given in table 2.

Table 2. Technology of task definition of management and decision-making as part of CES design

Stages	Stages content
Stage No. 1. Theoretical research	System description and CES models construction CES models analysis CES management synthesis (optimization) task Decision stability study
Stage No. 2. Models construction	Models identification Simulation experiments
Stage No. 3. Implementation	Project efficiency analysis and deployment

The choice of a specific method (or suite of methods) in order to solve a problem depends on the quantity and quality of available information. Such data are required for the implementation of the scientifically substantiated choice concept. It can be divided into four categories: information on alternatives, information on choice criteria, information of preferences, and information of the multitude of solvable tasks.

It should be specified that the efficiency indicator identifies the quantitative degree of attaining the goal, and the efficiency criterion is a certain rule that helps choose the most preferable CES variant based on the efficiency indicator.

The decision-making itself is an important stage of the choice process. This process is complex and multi-staged. It is though poorly covered in papers dedicated to decision-making.

3. Decision-making procedure used in the development of complex engineering systems

Let us consider the decision-making process involved in the development of engineering solutions. GOST ISO 15288-2002 has introduced the concept of «project processes» that include:

– project planning process;
– process evaluation process;

– project control process;
– decision-making process;
– risk management process;
– configuration management process;
– information management process.

Project processes are used for establishment and implementation of plans, evaluation of project progress as compared to plan and project execution control up to its completion. Individual project processes can be performed at any point of the lifecycle and at any level of project hierarchy both in accordance with project plans, and in emergency mode. The level of accuracy and formalization of project processes depends on project complexity and project risks.

The planning of operations research, evaluation and control are the key processes for practically all types of management.

The purpose of the project evaluation management process is defining the project status. In the course of this process, on a regular basis or concurrently with important events, project progress evaluation and performance assessment are performed. In case of significant irregularities, evaluation results are brought to the attention of stakeholders in order to ensure adequate administrative action.

As a result of successful project evaluation:
– project performance indicators and evaluation results become available;
– project parties' roles, duties and authority adequacy is evaluated;
– adequacy of the resources and services required for project implementation is evaluated;
– project performance irregularities are analyzed;
– stakeholders are informed of the project status.

In system analysis, it is normally believed that choice itself is decision-making. However, having analyzed the project process elements, we can see that between the "project evaluation" and "decision-making" there is the "process control process" element.

The purpose of the project control process is to organize project plan performance and assurance of project performance according to plans and time schedule within the project budget and guaranteed engineering purposes implementation.

As a result of control, the following happens in the decision-making process:
– corrective actions are defined and performed, should project results not correspond to respective planned tasks;
– project replanning is initiated, if project goals and restrictions have changed, or assumptions made at planning turned out to be wrong;
– transition from one planned stage or event to another is authorized (provided the previous stage or event was successful);
– project goals are reached.

According to GOST ISO 15288-2002, the purpose of the decision-making process is to choose the alternative that most suits the project goals. This process represents the reaction to decision-making requests that arise over the course of the system's lifecycle. Those requests aim to reach specified, desirable or optimal results regardless of the nature or source of such requests. Alternative actions are analyzed and the direction is chosen. The decisions and their substantiations are documented for future decision-making support.

As a result of successful decision-making:
– the decision-making strategy is defined;
– possible alternative actions are identified;
– the most preferable action is chosen;
– the decision taken, its substantiation and assumptions are documented and brought to the attention of stakeholders.

The decision-making process is a process that results in the solution to the defined problem. A significant number of scientific papers is dedicated to the decision-making theory. In general, from the process point of view, the decision-making process is well analyzed in a guidance paper published by the Novosibirsk State Technical University. The process can be represented as a series of decision stages [21]:

Stage 1. Goal identification.
Stage 2. Goal development.
Stage 3. Decisions generation.
Stage 4. Choice of decision.
Stage 5. Decisions evaluation.
Stage 6. Decision-making.
Stage 7. Decision implementation.

Stage 1 is important and determinant as it answers the following questions: what problem and in what conditions must be solved; how it should be solved; what assets will be used to solve it.

At the second stage, system purposes are defined. The better the system purposes are defined, the easier it will be to choose the means to achieve them. The methodological foundation of the goal definition stage is the system analysis with the use of expert methods.

At the third stage, alternatives are generated, various ways of reaching the goal are found. Alternatives can be generated by means of brainstorming, scenario generation and business games.

The choice of solutions from a number of alternatives is made by the decision-maker at the fourth stage based on the generated criterion that helps judge if the goal has been met. The criterion of an alternative's usefulness may be any of its properties or a set of properties measured qualitatively or quantitatively. In order to describe the goal, several criteria are often introduced in such a way as to describe the goal as completely as possible. The criteria for solution selection are defined using expert analysis and mathematical statistics.

At the fifth stage, based on the alternatives evaluation model, that takes into account the current situation, goals, a multitude of restrictions, alternative solution, the available solutions are evaluated based on the decision-maker's preferences. This task can be completed under the conditions of uncertainty caused by the influence of external factors on the alternatives' evaluation that can be taken into account using well-known probability theory methods. If uncertainty is absent (in case of certainty) many decision-making tasks are solved through well-known optimization methods.

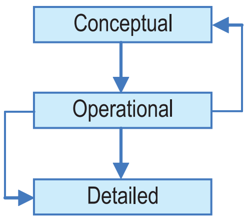
The sixth stage is the most important one, when it is required to choose the solution for its subsequent implementation using a certain algorithm that chooses the only solution that is superior in terms of a criterion or the optimality principle.

In case of decision-making based on many partial criteria (vectorial optimization tasks), additional difficulties arise in the identification of the best, from the decision-maker's point of view, compromise solution out of a number of allowable ones based on local measures. If it is required to identify the only best solution, then the set of allowable solutions comes down to a Pareto set and the search is made within it based on a certain scheme.

The seventh stage implements the achieved solution. The plan of solution implementation must answer the question as to who and what should do, by what means and within what timeframe. Responsible parties can be specified by means of work package performer appointment task, while the timeframes and work objects are specified by means of network planning and management.

Decision-making can be performed at various hierarchical levels. There are the conceptual, operational and detailed decision-making levels [22]. Table 2 sets forth the distinctive features of each of the levels of the overall decision-making hierarchy and their connections with regards to CES research.

Table 2. Decision levels hierarchy

Decision levels	Object of study	Goal of study	Model	Efficiency indicators and criteria
	System	Analysis of operations execution concepts. Identification of the list of subgoals and tasks, subsystems, their operating conditions. System «image» generation	Analytical	Operation goal attainment ratio. Suitability criterion. Adaptability criterion
	Subsystem	Analysis of methods of task performance by subsystems. Definition of the general images of subsystems and devices, general requirements to the quality of their elements	Simulation	Ratio of task performance by subsystems. Suitability criterion. Optimality criterion
	Element	Detailed analysis of the quality of elements	Statistical	Detailed analysis of the quality of elements

Notes. *In order to reach the set goal, a purposeful activity, an operation, is required. An operation is a system of purposeful actions that share a common design and a common goal. The concept of operation includes three defining factors [22]: 1) human control activities (decision-maker) that organize the operation by choosing a rational way of using active means in order to achieve the operation's goals; 2) active means (engineering systems, resources) at the disposal of the managerial body and used in the operation in accordance with the chosen method (management strategy); 3) other means (systems) that directly interact with the active means.*

Thus, in the course of research of primary operation performance concepts, definition of the preliminary list of subtasks of operations and purposes of subsystems of a complex engineering system and development of its conceptual design, it is required to repeatedly and promptly solve the synthesis task trough analysis in order to eliminate the demonstrably worse alternatives. For that purpose, conceptual models are used.

At the operational level of research, when the subsystem goals, tasks and operating conditions have been defined and the rational logic of operation progress has been identified, additional factors can be taken into consideration and a more complex model can be designed in order to evaluate the performance of subsystems of a complex engineering system. The result of this stage is the consolidated concept of subsystems and means, as well as the general requirements to the quality of their elements. The models used at the operational level are usually implemented as complex simulation models. At the detailed research level, elaborate mathematical, physical and full-scale models are created in order to analyze the quality of subsystem elements. As this stage is normally evidence-based and uses the methods of experiment design, mathematical statistics, etc., this level's models are predominantly statistical. This three-level decomposition of the overall decision-making task allows establishing the viability of the suggested procedure performance concept and generate an integrated (systemic) vision of decision-making operation and process both in terms of their goal, and subject to the capabilities of other subsystems and assets. They enable the evaluation of the decisions taken at lower levels using well-known methods of operations research (conditions and goals are well defined).

Conclusions

1. The decision-making procedure is a complex event and one of the main processes of CES design at all lifecycle stages. Decision-making is the result of a series of events: goal identification, generation of new and alternative ideas, grounded decisions, evaluation of possible solutions, decision-making and implementation.

2. The development of efficient CES objects normally comes down to choosing one or more alternatives out of a number of specified ones. Making grounded decisions requires a clear goal, tasks and criteria (quality indicators) that are used for the evaluation of a set of alternatives.

References

1. **Lindsey P., Norman D.** Human Information Processing. Moscow. Mir, 1974. – 550 p.

2. **Azgaldov G.G., Raikhman E.P.** On Qualimetry. Moscow. Izdatelstvo standartov, 1973. – 172 p.

3. **Azgaldov G.G.** Theory and Practice of Product Quality Evaluation. Foundations of Qualimetry. Moscow. Ekonomika, 1982. – 256 p.

4. **Andrianov Yu.M.** Qualimetry of Automotive Products. Leningrad. Mashinostroenie, 1990. – 271 p.

5. Methods of Qualimetry in Engineering / Vladimirov, A.I., Kershenbaum, V.Ya., Polikarpov, M.P. et al.; Edited by **Kershenbaum, V.Ya., Khvastunov, R.V.**. Moscow. Tekhnoveftegaz, 1999. – 211 p.

6. **Fediukin V.K., Durnev V.D., Lebedev V.G.** Industrial Products Evaluation and Quality Management Methods. Textbook – Moscow. Filin Information and Publishing House, Rilant, 2000. – 328 p.

7. **Fediukin V.K.** Qualimetry. Saint-Petersburg. SPbGIEU, 2009. Moscow. – 365 p.

8. **Kirillov V.I.** Qualimetry and System Analysis. – Minsk. Novoie znanie: Moscow. INFRA-M, 2012. – 440 p.

9. **Semionov S.S., Kharchev V.N., Ioffin A.I.** Weapon System Performance Evaluation as a Significant Factor of its Development // Voienny Parad. – 1995 – № 1-2. – P. 174-176 (P. 87-89 in English).

10. **Semionov S.S., Kharchev V.N., Ioffin A.I.** Performance Evaluation of Weapon Systems and Hardware. – Moscow. Radio i sviaz, 2004. – 552 p.

11. Semionov S.S. Performance Evaluation of the Guidance Systems of Air-to-Surface Aircraft Weapon Systems // Vestnik kompiuternykh i informatsionnykh tekhnologiy. – 2006. – No. 8 – P. 7-11; No. 9 – P. 13-23; No. 10 – P. 12-18.

12. Semionov S.S., Shcherbinin V.V. Method of Performance Evaluation of the Guidance Systems of Guided Aerial Bombs // Voprosi oboronnoy tekhniki. Ser. 9. Special control systems, tracking drives and their elements. Moscow. FGUP NTTs Informtekhnika, 2010. – Issue 1 (242) – 2 (243). – 471 p. – P. 29-32.

13. **Semionov S.S.** Experience of Scientific Recognition of New Methods of Weapon Systems and Hardware Performance Evaluation through the Example of Guided Aerial Bombs // Boyepripasy. – 2007. – No. 5-6. – 214 p.

14. Spirkin A.G. Fundamentals of Philosophy. Moscow. Voenizdat, 1988. – 592 p. – P. 179.

15. Tsvirkun A.D. Structure of Complex Systems. Moscow. Sovietskoie radio, 1975. – 200 p.

16. **Prangishvili I.V.** System Approach and Systemic Consistency. Moscow. Sinteg, 2000. – 528 p.

17. GOST R ISO/IEC 15288 – 2005. Russian National Standard. Information Technology. System Engineering. ISO/IEC 15288:2002. System engineering – System life cycle processes (IDT). – Moscow. Federal Agency for Technical Regulation and Metrology, 2006. – 54 p.

18. **Polovinkin V., Dyshkantiuk A.** Systemic Approach to Naval Weapon Systems Lifecycle Evaluation and Implementation Methods // Morskoy sbornik. – 2009. – No. 7. – P. 23-28.

19. **Raiffa H.** Decision Analysis (Introductory Lectures on Choices Under Uncertainty). Moscow. Nauka, Main office of physics and mathematics literature, 1977. – 408 p.

20. **Andreichikov A.V., Andreichikova O.N.** System Analysis of Strategic Decisions in Innovation Theory. Mathematical, heuristic and intellectual methods of system analysis and innovation synergy. – Moscow. Knizhny dom LIBROKOM, 2013. – 304 p.

21. **Samkov T.D.** Theory of Decision-Making: Lecture Notes. – Novosibirsk: – NGTU, 2010. – 107 p.

22. Technology Dependability and Efficiency: Reference book. Efficiency of engineering systems / Edited by **Utkin, V.F., Kriuchkov, Yu.V.** Moscow. Machinostroenie, 1988. – 328 p.