

Managing Uncertainty in Civil Aviation Complex Technical Systems Development Projects

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Abstract: The effective management of projects for the creation of the Complex Technical Systems of Civil Aviation Type (CTS-CAT) remains one of the key problems in the field of high-tech mechanical engineering. The high complexity of such systems and their uniqueness cause significant uncertainty at all stages of the life cycle, which can lead to financial losses, delays in work performance and a decrease in the product's competitiveness. The purpose of the study is to determine the nature of uncertainty transformation in a typical CTS-CAT creation project and to formalize its dependence on the stages and steps of the life cycle. The present study was based on the analysis of literature sources, comparison of the life cycle models of CTS-CAT and Information Technology (IT) projects, as well as conducting expert assessments using the Delphi method and correlation analysis. As a result of the research, a typical three-stage, eight-step life cycle model of a complex technical system of civil aviation type with the Boundaries Of Critical Decisions Approval (BCDA) was developed and adapted to the uncertainty factors assessment. The results obtained allow for improving the process of uncertainty management in the projects to create the CTS-CAT, which will contribute to increasing the effectiveness of risk management and improving the results of implementing aircraft construction projects.

Keywords: system engineering, projects management, complex technical system, uncertainty, uncertainty cone, high-tech mechanical engineering.

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1. Introduction

The effective management of projects to create the CTS-CAT remains a key challenge for world leaders in high-tech engineering. The significant complexity of such systems and their uniqueness lead to substantial uncertainty at all stages of the life cycle, from the idea and conceptual design through development and production to commissioning.

The main approaches used in modern practice for overcoming these challenges are project management and system engineering methodologies. They allow for the structuring of development processes, coordinating stakeholders' interests and reducing risks. Nevertheless, in conditions of high complexity of projects, which are typical for the aviation industry, the uncertainty factors become critical.

Unaccounted uncertainty leads to significant financial losses, delays in work execution and reduction of product competitiveness. In the case of the CTS-CAT, such as modern passenger aircraft or unmanned aerial vehicles designed for civilian missions, potential losses can reach billions of U.S. dollars, jeopardizing the success of the entire project. Thus, the analysis and evaluation of the nature of uncertainty manifestation in CTS-CAT creation projects constitute not only an applied but also a methodological problem. Despite the well-known "cone of uncertainty" model proposed for IT projects (Boehm, 1981), the question of its applicability to long-term, capital-intensive engineering programs remains open.

The research question of this study is to determine whether the uncertainty reduction pattern characteristic of IT projects is preserved in CTS-CAT creation projects and how this dynamic correlates with the structure of their life cycle and the BCDA. The purpose of the study is to determine the nature of uncertainty transformation in a typical CTS-CAT creation project and to formalize its dependence on the life cycle stages and steps.

The following tasks were set for the goal achievement:

- To analyze the most representative information from literary sources regarding the manifestations of uncertainty factors in modern projects, and to identify the impact of uncertainty on the most important parameters of the project.
- To analyze and specify the regularity of uncertainty distribution in IT project activities to use it as an analogue in typical CTS-CAT projects.
- Methodically ensure, organize and correctly implement the solution of expert evaluation problems, which have been formulated in the research.
- To develop a formalized project-system model representing the life cycle of the CTS-CAT.
- To identify areas-zones of the greatest concentration of uncertainty in the CTS-CAT projects and the typical dynamics of their reduction.

Taking the above into account, the following research hypotheses were formulated in the study.

H1. The pattern of uncertainty reduction in projects for the creation of CTS-CAT differs from the well-known “cone of uncertainty” model proposed for IT projects.

H2. The primary reduction of uncertainty in projects for the creation of CTS-CAT is structurally associated with the BCDA, rather than with the uniform linear progression of project implementation over time.

2. Literature Review

2.1. Peculiarities of Presentation of Complex Technical System Creation Project through Modeling of its Life Cycle

The Complex Technical Systems (CTS) include products created in high-tech industries such as aircraft, missiles, weapon systems, and unmanned aerial vehicles. Their production is characterized by high labor intensity, significant resource consumption and specific costs. A key feature of the CTS is its uniqueness, which is manifested in the absence of similar systems in the past, new properties and unique characteristics, as well as the ability to solve problems and achieve goals unavailable to the predecessors. The creation of the CTS requires a significant amount of scientific research and research development work, which is often of a fundamental nature.

Separately, among the CTS, it can be marked out the CTS-CAT, which includes passenger aircraft, cargo aircraft and present-day unmanned aircraft designated for civilian use. A special feature of the CTS-CAT is increased requirements for safety, economic efficiency, environmental friendliness and reliability. The creation of such systems involves an in-depth analysis of the market and interested party’s needs, a high level of standardization and certification, as well as the use of present-day materials and technologies to achieve energy efficiency and reduce operating costs.

The accepted approach to the formal representation of the CTS creation projects is to model them through their life cycles. There are different definitions of the concept of the “system life cycle”, one of the generally accepted ones can be considered as follows: “system life cycle is the step-by-step evolution of the creating system from conception through the development to the production, operation and further elimination” (Kossiakoff et al., 2011). Life cycle use allows us to systematize the project management processes, ensuring the control of task performance and achievement of goals at every stage. In the early stages of development of the project management methodology and system engineering, the life cycle development model of the system was presented in the form of a linear diagram with sequentially located stages of the life cycle. Later, the understanding came that there cannot exist clear boundaries between separate periods (stages, phases, steps), they are rather presented as overlapping with each other. The transition from one stage to another, from one state of the system to another, began to be associated not with “physical time”, but rather with the “logical” way of the system’s development. Such a circumstance was also reflected in the form of the “cascade type model” presentation. Its drawback was the real impossibility of iteration to previous stages in case of failure to achieve the desired result (Royce, 1970). This drawback was eliminated by the spiral type of model proposed by Barry Boehm (Boehm and Hansen, 2000; Boehm et al., 2014). In it, the model of work presentation, stages and steps, on a time scale, was replaced by their presentation in a spiral form, with periodic repetition. Such an approach permits us to identify clearly the need to take into account possible iterations during the implementation of complex projects. Various types of spiral models are cited by several authors, including Kossiakoff et al. (2011) and Kryvov et al. (2022). In the latest publication, a “spiral-vortex” three-dimensional model of the CTS life cycle is presented, which, in addition to the work iterations during the life cycle evolution, demonstrates changes in the uncertainty of the system project from “max” at the beginning of the project to a realistic “min” at the end of the project.

Another type of life cycle model representation was proposed by Forsberg and Mooz (1991), which has the shape of the letter “V”, in fact, it is a linear diagram of the life cycle bent at the point of system transition from the virtual to the physical state. Obviously, there are generally accepted graphical representations of the CTS life cycle model. In practical activities, the most common representations are simplified: a line diagram, a line diagram with overlap, and emphasis on verbal representation.

The life cycle of CTS creation is typically described in regulatory documents as a sequence of four to six stages. Different standards present similar but not identical stage structures. NATO's AAP-20 (2015) includes six stages: concept, development, production, disposal, support, and decommissioning, along with the pre-concept phase. Ukraine's standard DSTU V-P 15.004:2019 also lists six stages: conception, development, production, use, support and withdrawal. International civil standards (ISO/IEC/IEEE, 2015; ISO/IEC TR 24748-2, 2011) follow a similar pattern: order, development, production, use, support and decommissioning. In contrast, DSTU 3974-2000 focuses on design documentation stages: technical proposal, sketch project, technical project and working design documentation of prototypes.

So, despite some differences in the names of stages of the system's life cycle, which are determined by the features of the system's entities, their application areas and complexity levels, the general approach to the system's life cycle presentation remains the same. It consists of a verbal, if possible, graphic presentation of logically connected stages (phases, steps) that characterize the development of the CTS life cycle. These boundaries are determined based on the features and specifics of each type of CTS individually.

2.2. Manifestations of Uncertainty During Project Development

The manifestations of uncertainty factors are investigated in many scientific works. Uncertainty is considered an integral component of any project because it arises from limited information, making it difficult to predict outcomes and choose the most optimal ways to achieve goals. It can relate to both internal aspects, such as limited resources or technical difficulties, and external aspects, such as changes in legislation or fluctuations in market conditions (Perminova et al., 2008; Cleden, 2017). Pich et al. (2002) emphasize that uncertainty can be both a source of risks and open up new opportunities for the project. The works of Blanchard and Fabrycky (2010), deWeck et al. (2011), Cleden (2017) emphasize the importance of early identification of sources of uncertainty and the need for active systematic monitoring of uncertainty throughout the project.

It is a well known fact that as projects become more complicated, the manifestation of uncertainty factors increases, and their greatest degree corresponds to the early stages of such projects, decreasing as the project life cycle develops. Nevertheless, research in the field of the relationship between uncertainty manifestation during project development is extremely limited. The most well known approach in this area is the "cone of uncertainty" model proposed by Boehm (1981) and further developed by McConnell (2006). This model demonstrates that, even at the initial phase of an IT project implementation, the accuracy of parameter estimation increases significantly: during approximately the first third of the project duration, the range of possible deviations is reduced from about $4\times$ to $1.25\times$. Thus, the evolution of the degree of uncertainty is directly associated with the progressive refinement of estimates for the scope of work, costs, and functionality.

Within the framework of this study, uncertainty is defined as the degree of incompleteness and variability of information regarding project parameters (resources, schedule, cost, and technical characteristics) that affects the validity of managerial decisions at the corresponding stage of the CTS-CAT life cycle. Unlike risk, which involves the assessment of the probability and consequences of an identified event, uncertainty is interpreted as a broader state of insufficient determinacy of project parameters prior to their stabilization. For the quantitative representation of uncertainty, a normalized scale $[0; 1]$ was applied, where "0" corresponds to complete uncertainty (absence of stabilized parameters and a wide range of possible deviations), and "1" corresponds to a state of maximum determinacy at the respective stage. The measurement was carried out as an expert assessment of the degree of parameter determinacy at the beginning and at the end of each interval between the BCDA.

2.3. The Problem of Peculiarities of Uncertainty Manifestation in CTS-CAT Projects

Obviously, the graphical representation presented in the works of Boehm (1981) and McConnell (2006) in the form of the "cone of uncertainty" cannot be directly applied to the assessment of CTS projects, in particular CTS-CAT projects. However, the approach of taking into account the uncertainty factors during the project development can be considered quite productive.

In addition, it is interesting to obtain some equivalent of the project uncertainty in natural terms. The main goal of the research is to assess the general nature of the uncertainty curve for the CTS-CAT creation project, identify the areas of greatest uncertainty, and compare this with the main stages and steps of a typical aircraft construction project. This is necessary, first of all, for building a more effective risk management system in aircraft construction than currently exists, because uncertainty is the precursor to risk. Also, according to researchers Bedford and Cooke (2001) and Renn (2008), uncertainty, which is most often assessed using probabilistic statistical methods, can itself be considered a risk. In turn, new information about how uncertainty factors manifest in aircraft construction projects brings us closer to creating an uncertainty management strategy for these projects.

Thus, to develop an uncertainty management strategy as a decisive factor in improving project effectiveness, it is necessary to evaluate the nature of uncertainty in typical CTS-CAT creation projects and identify the areas where uncertainty can be most effectively reduced.

3. Methodology

The object of analysis was to assess how uncertainty factors manifest during the implementation of the CTS-CAT creation projects. The main difficulty of this task was its atypical, interdisciplinary nature, which made the process of selecting experts from various categories and specializations complex. This, in turn, made it difficult to develop and implement communication conditions for specialists from various fields.

One stage of the solution involved organizing collective participation among experts from various specializations to develop a formalized project-system model representing the life cycle of the CTS-CAT. During this lengthy process, the meaningful concepts and boundaries of using the term “uncertainty” in project management and system engineering were clarified. Based on the results of expert consultations, a “qualification table for uncertainty assessment in the CTS-CAT projects” was formed (see Table 1).

Table 1. Expert specialization for CTS-CAT life cycle stages and engineering activities

№	Type of activity	Category and specialization of experts	Key stages and steps of the CTS-CAT life cycle				
			00-02	02-05	05-08	08-10	10-14
1	Operational, management	Marketers, economists, analysts	V	-	-	-	V
2	Project management + system engineering	Leading design engineers of promising projects, economists of promising projects	V	V	V	V	V
3	System engineering	Leading design engineers for design of the CTS-CAT and its subsystems	-	V	V	V	V
4	System engineering	Heads of design units, chief designers	-	V	V	V	-
5	System engineering + project management	Chief technologists, technologist-engineers of the project organization	V	V	V	V	V
6	System engineering	Leading engineers - mass production specialists	-	V	V	V	-
7	System engineering	CTS-CAT testers, operators	V	V	V	-	V
8	System engineering	Disposal specialists	V	-	-	-	V

Formulated during the BCDA work, their meaningful content enabled participants to engage more effectively in future expert assessments of the manifestation of uncertainty factors typical of the CTS-CAT project creation.

At the next stage of the study, expert assessments of the manifestation of uncertainty factors within the BCDA intervals were conducted. For this purpose, a modified Delphi method was applied, supplemented by elements of brainstorming. The procedure was based on the classical approach to structured expert judgment consensus (Dalkey and Helmer, 1963; Dalkey, 1969) and its modern interpretations aimed at ensuring reliability and achieving consensus (Hsu and Sandford, 2007) and was adapted to the interdisciplinary nature of the research. The expert panel consisted of 25 specialists with practical experience in CTS-CAT creation projects (with an average of more than 15 years of professional experience). The distribution by specialization was as follows: 5 representatives of operational management (marketing, economic analysis), 7 project managers and leading engineers for prospective developments, 5 systems engineers and designers, 5 production technologists and 3 specialists in testing and operations.

The selection of experts was carried out according to the following criteria:

- Experience of participation in at least one CTS-CAT creation project throughout its full life cycle.
- Experience in decision-making at stages corresponding to the relevant BCDA.
- Professional specialization relevant to specific life cycle intervals.

The procedure included three rounds with controlled feedback. In the first round, experts independently assessed the degree of uncertainty within the intervals between the BCDA using a normalized scale (0;1) throughout the entire CTS-CAT life cycle and determined the natural equivalent of possible deviations. In the second round, they were provided with aggregated statistical indicators (median, interquartile range), after which they were allowed to revise their own assessments. The third round was conducted to stabilize the results. The survey was conducted in accordance with the principle of anonymity, and feedback was provided only in aggregated statistical form.

In this study, the natural equivalent of uncertainty is considered a generalized relative indicator of the potential variability of key project parameters (cost, labor intensity, scope of work) and reflects the possible multiplicity of their deviation from the final stabilized level. The baseline value (1) corresponds to the state of maximum determinacy after BCDA 14. The other values (8, 5, 2, 1.2) are interpreted as a consensual expert estimate of the potential multiplicity of deviation from this stabilized level. The indicator was derived by aggregating experts median assessments of the maximum possible variation in key project parameters at each stage. The indicator is of an indicative nature and is intended for comparative analysis of the dynamics of uncertainty across the life cycle stages of the project rather than for direct financial forecasting.

The aggregation of results was performed using median values. The level of agreement of the uncertainty degree indicators was evaluated by the Interquartile Range (IQR), while the selection of the most significant BCDA for assessing the degrees of uncertainty was carried out using Kendall’s coefficient of concordance (W). Consensus was considered achieved under the conditions $IQR \leq 0.15$ and $W \geq 0.7$. According to the results of the final round, Kendall’s W was 0.74, which indicates a sufficient level of agreement among the expert assessments. A more detailed description of the expert

assessment procedure and its methodological justification is presented in the authors' previous studies (Kryvova, 2024; Kryvova, 2025).

To examine the relationship between the degree of uncertainty and the successive BCDA intervals, a non-parametric correlation analysis was conducted. The variables considered were the ordinal number of the BCDA interval within the life cycle structure and the median value of the uncertainty level obtained from expert assessments (normalized scale (0;1) for the corresponding interval). Taking into account the expert-based nature of the data and their ordinal character, Spearman's rank correlation coefficient (ρ) was applied. The statistical significance was tested using a two-tailed criterion at a significance level of $\alpha = 0.05$. The obtained coefficient value ($\rho = -0.84$) indicates the presence of a pronounced negative monotonic trend in the decrease of the uncertainty level as the project progresses across successive BCDA intervals. At the same time, considering the expert-based nature of the initial data, the results of the correlation analysis should be interpreted as confirmation of a general trend rather than as an exact quantitative statistical relationship.

Within the framework of the study, the formulated hypotheses H1-H2 were tested. Hypothesis (H1) was evaluated through a comparative analysis of the configuration of the obtained uncertainty curve with the well-known IT "cone of uncertainty" model. Hypothesis (H2) was examined by analyzing the relationship between the level of uncertainty and the sequence of BCDA intervals, including the application of rank correlation analysis and structural analysis of the intensity of changes between adjacent intervals.

4. Results and Discussions

As mentioned above, there are several forms of the CTS-CAT life cycle representation. It is also well known that the largest manufacturers of aviation equipment prefer to develop their own corporate documentation for this field, tailored to the specifics of their activities.

Some approaches in this area are known; they were, to some extent, taken into account, formalized and templated based on the objectives of the present study. Therefore, for the sake of clarity, the typical life cycle of the CTS-CAT was supplemented with the "pre-project stage" to emphasize the two main ways of meeting the needs of the external environment (see Fig. 1).

First, when the requirements to meet the need are formed by an external customer. This is most often done by a centralized state structure, such as the Ministry of Defense or the Ministry of Emergency Situations. It can also be an external customer that announces a tender and sets its conditions (see 1 in the Fig. 1). The second one is the initiative path of the designer, when the operational management initiates, within frames of the implementation of the organization development strategy, a "business idea" to satisfy any identified need that corresponds to the profile of the organization's activities (see 1 in the Fig. 1). Thus, it was emphasized that the task of operational management of organization even before the initiation of the project is the "business idea" justification, which is presented both from the point of view of the presence of a significant forecasted need, and from the point of view of its principle implementation within the framework of available opportunities. This period was foreseen, but according to the accepted practice among aviation specialists, it was not included in the life cycle. For clarity, it was marked as "pre-project stage".

Further, for the sake of simplification and clarity of presentation, a stage-step form of presentation of the CTS-CAT life cycle was adopted, which included three main stages: pre-development, development, and post-development. Thus, the importance of the initial two stages was emphasized. By consensus among involved experts, the 14 most significant milestones in the development of the CTS-CAT creation project were adopted. They were defined as BCDA. The BCDA framework is conceptually aligned with the stage-gate logic embedded in standardized system life cycle models (ISO/IEC/IEEE, 2015; NATO, 2015). At the same time, its structure has been adapted to reflect the specific characteristics of CTS-CAT creation projects. To ensure methodological transparency, Table 2 presents the correspondence between the BCDA and the life cycle stages defined in the standardized frameworks (ISO/IEC/IEEE, 2015; NATO, 2015). Therefore, the BCDA does not replace the standard life cycle structure but rather refines it through formalized decision points, enabling the linkage of uncertainty dynamics to specific managerial milestones rather than solely to the project timeline. This ensures the integration of the proposed model with internationally recognized regulatory frameworks.

It is worth noting that the CTS-CAT life cycle scheme presented in this study is conceptual. In practical corporate documentation, the nomenclature, number of stages, phases, control points, and BCDA may vary considerably. Nevertheless, the underlying logic and structural principles of constructing such models are comparable. Accordingly, the typical three-stage, eight-step life cycle model of the CTS-CAT with BCDA, presented in Fig. 1, could serve as a basis for analyzing the manifestation of uncertainties at various stages and steps of the CTS-CAT project's development.

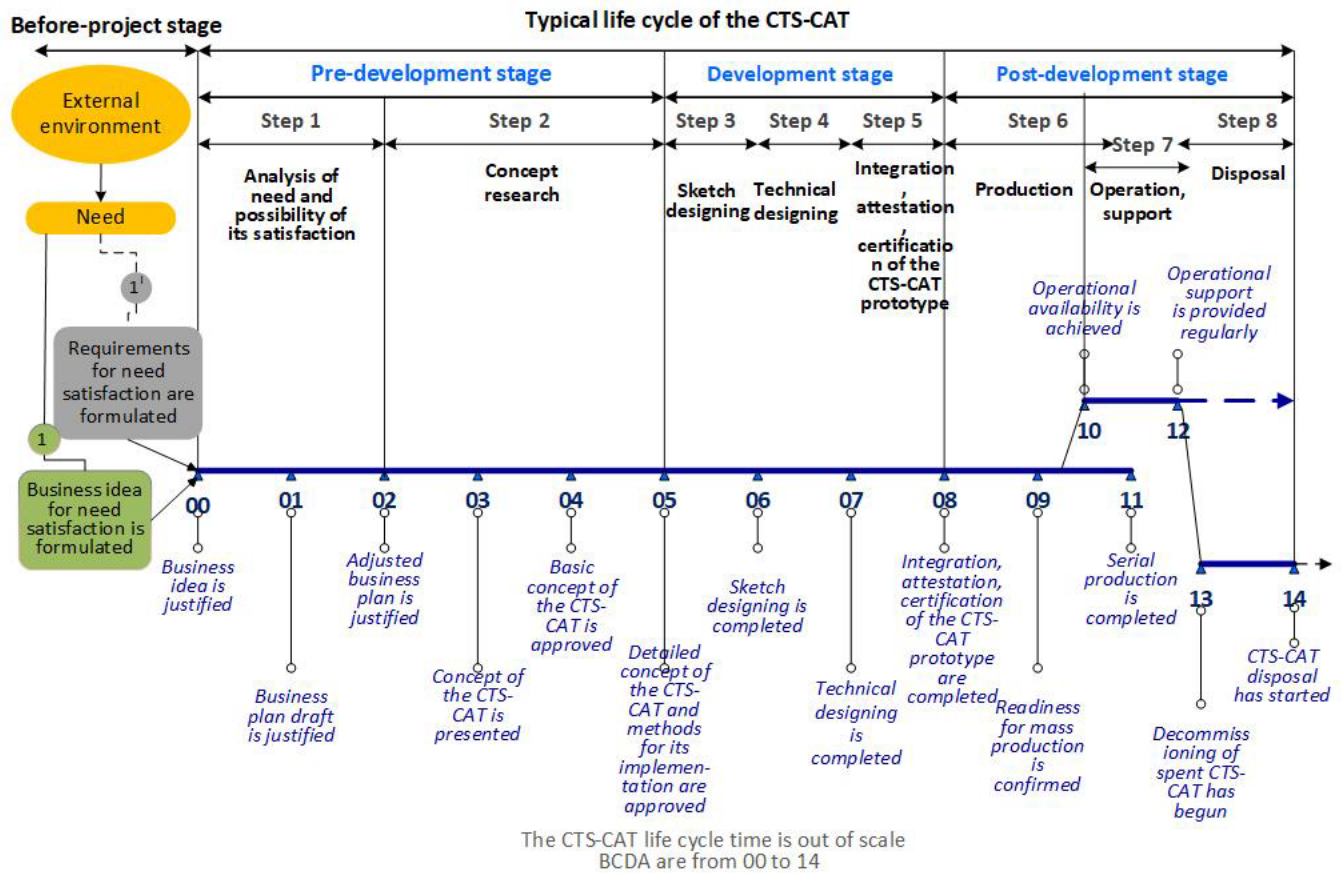


Fig. 1. Three-stage, eight-step CTS-CAT life cycle model with uncertainty factors identified at each stage

A typical three-stage, eight-step model of the CTS-CAT life cycle with the BCDA (00-14), adapted to the assessment of uncertainty factors identified at various stages or steps of its presentation. At the “pre-project stage” (1’), the need is formalized by the customer in the form of requirements and is usually presented in tender proposals. (1-), the need is identified by the business environment.

The participation of experts from various specializations in the model’s development ensured a unified understanding of the applied project systems engineering’s essence of uncertainty, which provided the foundation for subsequent quantitative assessments. As a result of the expert evaluations and their processing, an understanding was obtained of the relationship between the main stages and steps of the CTS-CAT project life cycle and the nature of uncertainty factor manifestation within them (Table 3).

Table 2. Correspondence Between the BCDA and the standard life cycle stages

BCDA	Content of the decision boundary	Corresponding stage (ISO/IEC/IEEE 15288)	Corresponding stage (NATO AAP-20)
00	Formalization of the need/business idea	Stakeholder needs and requirements	Concept
02	Concept validation	System requirements definition	Concept/development
05	Completion of preliminary design	Architectural design	Development
08	Completion of detailed design	Detailed design and implementation	Development/production Preparation
10	Integration and testing	Integration and verification	Production
14	Transfer to operation and support	Operation and support	In-Service

The intervals of uncertainty reduction presented in Table 3 were formed based on aggregated results from three Delphi rounds. The definition and calculation procedure of the natural equivalent of uncertainty are provided in Section 3 (Methodology). The values 8, 5, 2, 1.2, and 1 represent consensual expert estimates of the relative multiplicity of potential

deviations compared with the final stabilized stage (baseline = 1). Consequently, Table 3 represents a formalized expert model of the uncertainty dynamics of a typical CTS-CAT project, constructed based on agreed assessments of an interdisciplinary panel. Graphically, by analogy with the approach of Boehm (1998) and McConnell (2006), the results are presented in Fig. 2.

Table 3. Life Cycle Stages and Uncertainty Factors in CTS-CAT Projects

No.	Characteristic steps of the CTS-CAT complex, manifestation of uncertainty factors, which are separated by the BCDA	Reduction of uncertainty degree at the corresponding step from “0” to “1”, where “0” is complete uncertainty, “1” is complete certainty	Nature of dependence	Dynamics of change	The natural equivalent of uncertainty (scope of work, costs at the end of the step)
1	00-02 BCDA	0-0.15	Direct	Average	8
2	02-05 BCDA	0.15-0.35	Direct	Average	5
3	05-08 BCDA	0.35-0.8	Exponential	High	2
4	08-10 BCDA	0.8-0.95	Direct	Average	1.2
5	10-14 BCDA	0.95-0.99	Direct	Very low	1

Considering and analyzing the data shown in Fig. 1, Table 3, and Fig. 2, the following can be concluded:

- The general concept of uncertainty reduction throughout project development is relevant to CTS-CAT projects; however, its spatial–temporal configuration and the concentration of uncertainty manifestations differ substantially from the classical model proposed for IT projects.

- The first fundamental difference is the greater deviation of the estimated natural equivalents of uncertainty (on average by a factor of two or more) expressed in terms of the scope of work and costs.

- The second difference is the clearly predicted unevenness of the rates of change in the degrees of uncertainty - the main drop in uncertainty should occur at the “development” stage, the following steps: sketch, technical designing, integration between BCDA 05- BCDA 08.

- The third fundamental difference lies in the different shapes of the curves, which are caused by a large concentration of uncertainty factors at the initial stages of the project: pre-development and development. Taking into account the long time frame of life activity of many aircraft construction projects, 40-50 years or more, the main portion of uncertainty manifestation is no more than 10% of the project duration. (Unlike the IT projects, where this indicator reaches 30%). Thus, a “cone of uncertainty” is more like an “uncertainty funnel of needle type”.

These results confirm hypothesis H1. The identified concentration of uncertainty reduction within specific BCDA intervals confirms hypothesis H2.

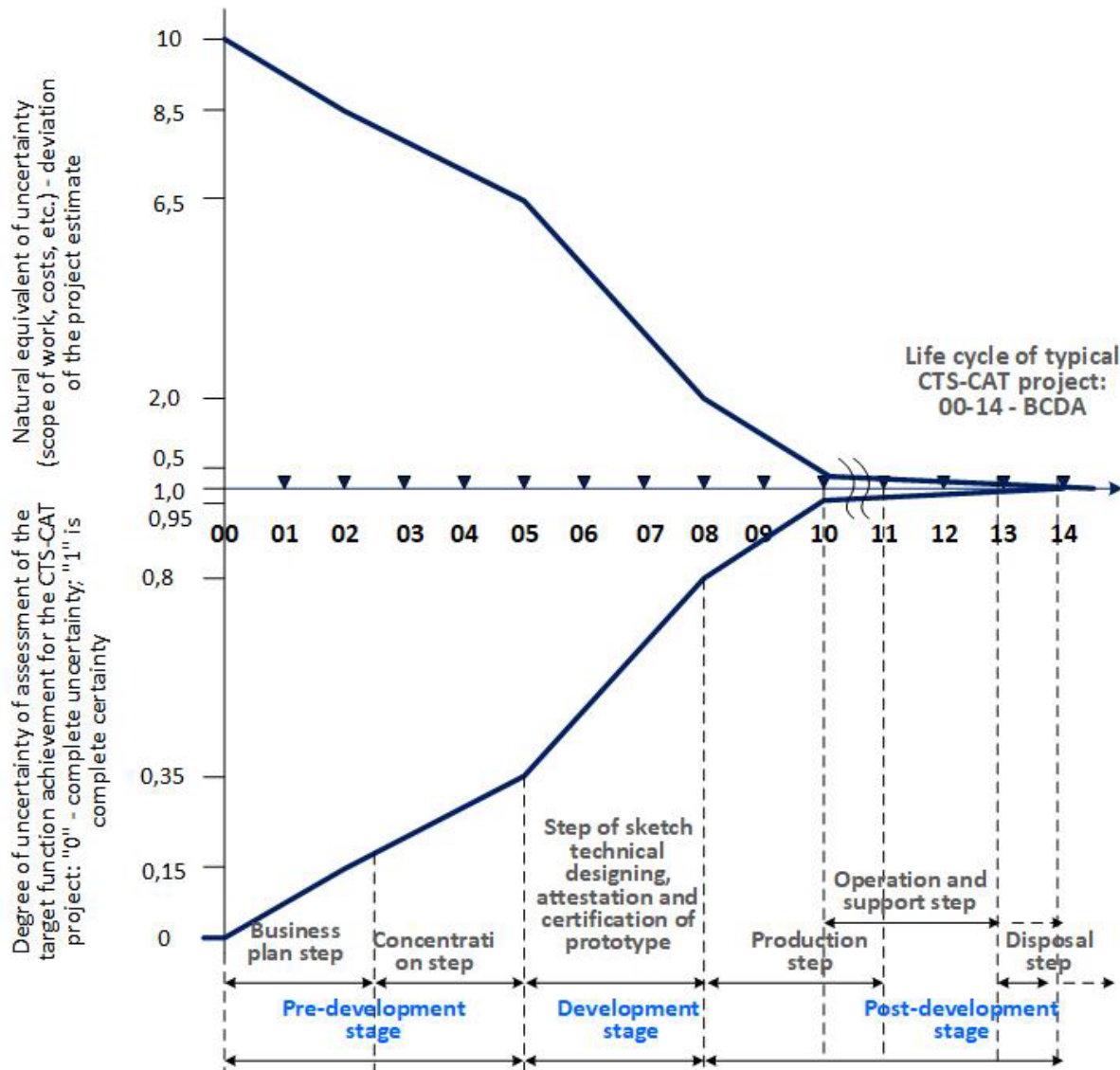


Fig. 2. Funnel-needle model of CTS-CAT project uncertainty based on expert assessments

Funnel-needle of a typical CTS-CAT project uncertainty, obtained based on expert assessments. The model is developed by analogy with the “cone of uncertainty” proposed by Boehm (1981) and McConnell (2006) for IT projects.

5. Conclusions, Limitations, and Recommendations

5.1. Conclusion

Despite the considerable attention devoted to improving the processes of creating CTS, in particular CTS-CAT, the problem of uncertainty management remains highly relevant. It is closely related to risk management and significantly affects the effectiveness of aircraft construction project implementation.

The conducted literature review has demonstrated the inadequacy of directly transferring the well-known uncertainty distribution model used in IT projects, the so-called “cone of uncertainty, to projects for the creation of complex technical systems, particularly civil aviation systems. At the same time, the analysis made it possible to clarify the content of uncertainty as a state of variability of project parameters prior to their stabilization during the life cycle development process and to demonstrate its direct impact on key project indicators, cost, schedule, scope of work, and technical characteristics.

In this study, a typical three-stage, eight-step life cycle model of CTS-CAT with BCDA was developed and practically tested, adapted to the assessment of uncertainty factors.

The proposed model is well aligned with current international regulatory frameworks in this field and makes it possible to relate the transformation of project parameter uncertainty not only to changes in the project state over time but also to specific managerial decision points.

The model proposed in this study represents an innovative contribution to improving the methodology of CTS-CAT development, particularly at the early project stages, since it allows:

- Identifying zones of the highest concentration of uncertainty and the typical dynamics of its reduction.
- Establishing that the maximum level of uncertainty is characteristic of the early “pre-development” and “development” stages, while its primary reduction occurs during the period of key engineering decision-making.
- Demonstrating that the configuration of the uncertainty transformation curve assumes a shape resembling a “needle-type funnel,” reflecting high initial variability of project parameters and their gradual stabilization as the project progresses.

It is widely recognized that assessing indicators used in models of this type involves certain methodological difficulties. In this study, an acceptable level of assessment validity was ensured through the application of a modified Delphi method. The procedure was based on the classical approach to structured expert judgment consensus and its modern interpretations aimed at ensuring reliability and achieving agreement, and it was adapted to the interdisciplinary nature of the research. The degree of agreement among expert assessments was determined using Kendall’s coefficient of concordance (W), subject to the conditions $IQR \leq 0.15$ and $W \geq 0.7$. In the final evaluation round, Kendall’s W reached 0.74.

Thus, the obtained results confirm the formulated research hypotheses and support the conclusion that the reduction of uncertainty in CTS-CAT creation projects has a structural character, primarily associated with critical decision boundaries rather than with the uniform passage of time.

The theoretical contribution of the study lies in clarifying the patterns of uncertainty transformation in long-term, knowledge-intensive engineering projects and substantiating the difference in their dynamics compared to IT projects. The methodological contribution consists of formalizing the relationship between the level of uncertainty and BCDA as institutionalized managerial decision boundaries. The practical significance of the results lies in the potential to use the proposed model as a methodological basis for improving risk management systems in aircraft construction and other high-tech mechanical engineering industries.

5.2. Limitations

The approach to uncertainty management proposed in this study, based on the CTS-CAT life cycle model with BCDA and adapted to the assessment of uncertainty factors, has certain limitations:

- The presented results are based on consensus expert assessments rather than on statistical analysis of completed projects.
- The model reflects a typical CTS-CAT project and may require adaptation for specific corporate or national programs.
- The natural equivalent of uncertainty is presented in relative form without detailed decomposition by cost structure.
- The nature and types of critical decisions made at the respective project boundaries were not separately analyzed or classified.

5.3. Recommendations

Despite the positive results, implementing the proposed model in the practice of the CTS-CAT project requires further research. Future studies should focus on empirically verifying the developed model using data from completed aircraft construction programs, developing quantitative tools to integrate uncertainty assessments into risk management systems, and refining methods for formalizing uncertainty in long-term engineering projects.

Further research should also address the typology, personalization, and interdisciplinary nature of critical decisions made during project development.

At the same time, taking the above into account, the results obtained provide a methodological foundation for the further development of approaches to uncertainty and risk management in CTS-CAT creation projects.

Author Contributions

Svitlana Kryvova contributed to conceptualization, development of the BCDA framework and life-cycle model, methodology design, organization of the Delphi study, data interpretation, manuscript drafting and editing. Sergii Trubachev contributed to the coordination of the expert panel, data collection, statistical analysis, and manuscript editing.

Constantine Zvorykin contributed to methodology refinement, visualization of results (figures and tables), and manuscript editing.

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References

- Bedford, T. and Cooke, R. M. (2001). *Uncertainty in the Risk Assessment Process: The Challenge of Making Reasonable Assumptions*. Cambridge, United Kingdom: Cambridge University Press, 19-20.
- Blanchard, B. S. and Fabrycky, W. J. (2010). *Systems Engineering and Analysis* (5th ed.). Upper Saddle River, New Jersey: Prentice Hall, 59-61.
- Boehm, B. Hansen, W. J. (2000). *Spiral Development: Experience, Principles, and Refinements*. CMU/SEI-2000-SR-008, 3-16.
- Boehm, B. W., Lane, J. A., Koolmanojwong, S., and Turner, R. (2014). *The Incremental Commitment Spiral Model: Principles and Practices for Successful Systems and Software*. Boston, Massachusetts: Addison-Wesley, 18-25.
- Boehm, B. W. (1981). *Software Engineering Economics*. Englewood Cliffs, New Jersey: Prentice Hall, 311.
- Cleden, D. (2017). *Managing Project Uncertainty*. London: Routledge, 23-25.
- Dalkey, N. and Helmer, O. (1963). An experimental application of the Delphi method to the use of experts. *Management Science*, 9(3), 458-467.
- Dalkey, N. (1969). *The Delphi Method: An Experimental Study of Group Opinion*. Santa Monica, California: RAND Corporation.
- de Weck, O. L., Roos, D., and Magee, C. L. (2011). *Engineering Systems: Meeting Human Needs in a Complex Technological World*. Cambridge, Massachusetts: MIT Press, 65-67.
- DSTU 3974-2000 (2000). System of product development and launching into manufacture. Procedures of experimental and design works. Basic principles. Kyiv: Derzhstandart of Ukraine, 12-13.
- DSTU V-P 15.004:2019 (2019). System of development and launching into manufacture of armament and military equipment. Life cycle stages of armament and military equipment. Kyiv: UkrNDNC, 4-10.
- Forsberg, K. and Mooz, H. (1991). The relationship of system engineering to the project cycle. *Proceedings of the National Council for Systems Engineering (NCOSE) Conference*, Chattanooga, Tennessee, 57-65.
- Hsu, C.C. and Sandford, B. A. (2007). The Delphi technique: Making sense of consensus. *Practical Assessment, Research & Evaluation*, 12(10), 1-8.
- ISO/IEC/IEEE 15288:2015 (2015). Systems and software engineering — System life cycle processes. Geneva: ISO, 14.
- ISO/IEC TR 24748-2:2011 (2011). Systems and software engineering — Life cycle management — Part 2: Guide to the application of ISO/IEC 15288. Geneva: ISO, 3.
- Kossiakoff, A., Sweet, W. N., Seymour, S. J., and Biemer, S. M. (2011). *Systems Engineering: Principles and Practice* (2nd ed.). Hoboken, New Jersey: Wiley, 70-78.
- Kryvova, S. (2025). Creation of complex technical systems considering the uncertainty factor. *Mechanics and Advanced Technologies*, 9(1), 104. doi: 10.20535/2521-1943.2025.9.1(104).316582.
- Kryvova, S. and Trubachev, S. (2024). Uncertainty in design and system engineering activities under the CTS creating. *Science and Technology Today*, 11(39), 914-926. doi: 10.52058/2786-6025-2024-11(39).
- Kryvov, H. O. Kryvova, S. H., Zvorykin, K. O., and Zubaniov, O. Y. (2022). *Fundamentals of Systems Engineering*. Kyiv: Igor Sikorsky Kyiv Polytechnic Institute, 101-102.
- McConnell, S. (2006). *Software Estimation: Demystifying the Black Art*. Redmond, Washington: Microsoft Press, 37.
- NATO (2015). AAP-20: NATO Programme Management Framework (NATO Life Cycle Model). Brussels: NATO Standardization Office, 40-42.
- Perminova, O., Gustafsson, M., and Wikström, K. (2008). Defining uncertainty in projects: A new perspective. *International Journal of Project Management*, 26(1), 73-79.
- Pich, M., Loch, C., and Meyer, A. (2002). On uncertainty, ambiguity, and complexity in project management. *Management Science*, 48(8), 1008-1023.
- Renn, O. (2008). *Risk Governance: Coping with Uncertainty in a Complex World*. London: Earthscan, 368.
- Royce, W. W. (1970). Managing the development of large software systems. *Proceedings of IEEE WESCON*, 14(8), 1-9.



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