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ADAPTIVE MODEL OF PROJECT MANAGEMENT IN THE FIELD OF INNOVATIVE ENGINEERING DEVELOPMENTS: INTEGRATING WATERFALL AND AGILE FOR DYNAMIC REQUIREMENTS

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The object of this study is project management in the field of innovative engineering developments and management of scientific projects under conditions of dynamic requirements, high complexity, and variable implementation deadlines. The study addressed the issue of insufficient flexibility of the Waterfall methodology for adapting to changing conditions and the lack of clear deadlines in the Agile methodology, which is critically important for engineering and scientific projects.

In the process of the study, the problems of conventional methodologies were analyzed, an expanded list of project input parameters were formed, and an analysis algorithm was devel-oped that makes it possible to determine the feasibility of using Waterfall and Agile elements at each stage of project implemen-tation. Using the advantages of the Waterfall and Agile meth-odologies and eliminating their shortcomings is possible within the framework of an adaptive model of scientific and innovative project management.

The results of the study show that the model devised provides effective resource management, reducing implementation deadlines and increasing stakeholder satisfaction. The integration of the Waterfall structure and Agile iterativeness makes it possible to avoid the shortcomings of each of the methodologies, ensuring greater adaptability and accuracy in achieving goals. The proposed model helps optimize project management under conditions of high uncertainty and changing market conditions.

The results could be used by companies to improve the management of engineering and scientific projects, especially in industries where rapid adaptation to changes and ensuring predictability of results are important. This study also contributes to the formation of a new approach to project management, which takes into account the specificity of modern innovative developments

Keywords: adaptive model, Waterfall, Agile, innovative engineering developments, scientific project management

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1. Introduction

Flexibility in managing engineering and scientific projects is the key to their successful implementation. At the same time, not all project management models are characterized by sufficient flexibility in the dynamic environment of implementing such projects. The integration of Waterfall and Agile, devising an adaptive model that combines the strengths of both approaches, makes it possible to solve the problem of insufficient flexibility of classical methods and the lack of clarity in Agile. This could ensure greater efficiency in project management, improve resource utilization, and allow companies to better cope with unpredictable changes. Given the high requirements for innovative engineering developments and the constantly changing market situation, the development and implementation of adaptive project management models are key to ensuring the competitiveness of conglomerates, corporations, and enterprises in the long term.

The need to design an adaptive project management system in the field of innovative engineering developments and scientific research involves the integration of Waterfall and Agile methodologies to ensure flexibility and efficiency of management processes, which is extremely important under the conditions of modern technological changes and a fast-paced business environment. Given the high speed of change, the growing complexity of engineering and scientific projects, and the need for rapid adaptation to new requirements, conventional management methodologies such as Waterfall may be ineffective. At the same time, flexible methods such as Agile, although they provide rapid adaptation, are not always suitable for large engineering and scientific projects that require a clear structure and predictability.

In this regard, research into this area is of great importance both for the scientific community and for the practical activities of conglomerates, corporations, and companies engaged in engineering and scientific developments. It could contribute to the formation of new approaches to project management that would meet the requirements of rapidly changing conditions, improve the financial and technological performance of conglomerates, corporations, and companies, and ensure their innovativeness.

2. Literature review and problem statement

Paper [1] reports the results of research on the integration of Waterfall and Agile methodologies as a modern approach to project management. It is shown that such integration

makes it possible to combine clear Waterfall planning with Agile flexibility, which contributes to resource optimization and effective risk management. However, issues related to the need to adapt organizational culture and the complexity of implementing a hybrid approach into conventional business processes remains unresolved. The likely reason is organizational barriers, lack of proper methodological support, and high costs of staff retraining. An option for overcoming these difficulties may be the phased implementation of hybrid methods with the involvement of external experts. This is the approach used in paper [2] but the need for careful planning and organization of processes remains a key challenge. All this gives grounds to argue that it is advisable to conduct a study aimed at considering methods for adapting organizations to hybrid project management approaches.

Paper [3] examines the transition from Waterfall to Agile, in particular the popularization of the approach after 2013 and the development of such variations as Scrum and Test-Driven Development. It is shown that Agile contributes to a rapid response to changing customer requirements and frequent product releases. However, questions remains unresolved regarding the effectiveness of Agile implementation in large organizations with established processes. The likely reason is the limitations of conventional corporate structures and the complexity of scaling Agile. An option to overcome this problem may be the gradual implementation of Agile in specific divisions of the company. This is the approach used in [4], which considers the adaptation of Agile in an insurance company in Saudi Arabia. However, even with such adaptation, there is still a need for organizational changes and changes in corporate culture. This indicates the feasibility of further research into the mechanisms for scaling Agile in large companies.

Paper [5] examines the impact of agile methodologies, such as Scrum and Kanban, on product management in a dynamic market. It is shown that these methods increase innovation and contribute to improving customer satisfaction. At the same time, the issue of adapting these methods in conservative industries, where conventional approaches have significant weight, remains open. The likely reason is psychological barriers and resistance to change from the side of management. An option to overcome such difficulties is to devise mixed methodologies that combine elements of conventional management and agile approaches. This is the approach considered in study [6], which analyzes adaptive project management (APM) as a way to minimize risks under uncertain conditions. However, the need for changes in conventional organizational structures remains a serious challenge. This indicates the feasibility of further research on APM adaptation strategies in different sectors of the economy.

In [7], the concept of adaptive project management is considered, in particular iterative development, which allows teams to quickly adapt to changes. It is shown that the use of quantitative methods, such as Monte Carlo modeling, contributes to making informed decisions and reducing risks. However, the issue of psychological barriers that can complicate the implementation of such approaches remains unresolved. The reason for this is the lack of readiness of personnel to work with such methods and the lack of proper support from management. An option to overcome these difficulties may be training personnel and the gradual introduction of quantitative methods at the level of small projects. This is the approach used in [8], which considers adaptive management in the field of protected areas. However, the issue of optimizing adaptation processes remains open, which confirms the feasibility of further research into this area.

Study [9] analyzes the application of adaptive project management in South African municipalities. It is shown that conventional methodologies such as Waterfall do not meet the requirements of high uncertainty, while APM allows for more effective risk management. However, the issue of integrating APM into regulated government structures with established rules and procedures remains unresolved. The likely reason is strict regulatory constraints and the need for significant changes in the legislative framework. An option to solve this problem may be the development of hybrid management models that take into account both regulatory requirements and adaptability to change. This approach is partially implemented in [10], which analyzes the choice between Waterfall and Agile depending on the type of project. However, even in this case, the issue of adaptation remains relevant, which confirms the need for further research on the development of adaptive management approaches for the public sector.

All this gives grounds to argue that it is advisable to conduct a study aimed at constructing effective mechanisms for integrating adaptive project management approaches in organizations with established processes. However, the cited scientific studies [4–7] do not pay enough attention to specific aspects of which elements of the Waterfall and Agile methodologies should be combined, and there is no clear algorithm for this combination. Most studies [4–7] are limited to a general description of the advantages and disadvantages of each of the methodologies, without offering specific recommendations on how to optimally integrate the elements of Waterfall and Agile within the framework of one project.

The literature review [1–10] demonstrates that the issue of adapting organizational culture when implementing hybrid and agile project management methods remains unresolved. Existing studies fragmentarily consider individual aspects of resistance to change, psychological barriers, and the need for management support, but there are no comprehensive models of organizational transformation. This indicates the need for further research aimed at developing strategies for changing corporate culture and mechanisms for overcoming resistance in different types of organizations.

In addition, my literature review revealed the lack of a systematic approach to methodological support for the implementation of hybrid methods. The issues of choosing appropriate tools, implementation sequences, and assessing effectiveness remains scattered within individual cases. It is necessary to devise a unified methodology for implementing hybrid approaches that would take into account the types of organizations, the level of process maturity, and the specificity of the industry.

The problem of scaling Agile in large companies with established processes requires special attention, as evidenced by research results [3, 4]. Despite individual examples of successful adaptation, a general scaling mechanism in rigid structures has not been formed. This requires further empirical research that would identify barriers to scaling, as well as propose adapted models for implementing Agile at the level of large organizations.

Separately, it is worth highlighting the openness of the issue of applying agile methods in conservative and highly regulated sectors, such as public administration or con-

ventional manufacturing industries. Studies [5–10] show the potential of adaptive management in such settings but specific strategies for adapting to legislative and regulatory constraints remains undescribed. This confirms the need to form hybrid management models that would combine the requirements of the regulatory environment with the flexibility of Agile/APM.

Finally, the review of publications indicates a lack of research focused on optimizing the processes of personnel retraining and the implementation of quantitative decision-making methods. There is a need to devise step-by-step programs for training personnel to work with new management approaches, taking into account their level of readiness, industry specificity, and organizational structure. The development of such programs can become one of the priority areas of further research in the field of adaptive project management.

In addition, no studies were found that would describe a step-by-step algorithm for combining these approaches in real projects, taking into account the specificity of different industries and types of projects. This indicates the need for further research that would develop a clear algorithm for integrating Waterfall and Agile, determine the optimal stages and processes for their combination, and also investigate how this combination affects the effectiveness of project implementation. I believe that such research is an important step for the practical application of hybrid project management methodologies in various fields.

The current development of scientific and engineering project management requires the implementation of innovative approaches that combine classical management methodologies with flexible (Agile, Scrum) and adaptive project management systems. Of particular importance is the PMLS approach – Project Management Learning System, which combines knowledge management and project management. This makes it possible to optimize decision-making processes and ensures adaptation to changing conditions of scientific and research activities.

The use of Agile in project management has shown significant effectiveness, especially in rapidly changing environments. However, these methods were designed to be applied at the team level, not at the project portfolio level, which creates a number of challenges. These include resource management, priority management, and the complexity of the management model for multiple Agile teams.

To reduce the risks associated with scientific research, it is necessary to devise an adaptive methodology for managing research projects. The basic philosophies and tools used in Agile could be modified to meet the needs of scientific research projects, especially with an emphasis on flexibility and prioritization of change. Case studies are an example of successful adaptation of agile methods. In them, collaboration between scientists and software developers demonstrates the effectiveness of agile project management in a scientific environment.

Scientific software development projects using Agile report that their testing is more effective than average compared to conventional approaches. However, the differences in approaches to requirements remains insignificant, which indicates the need for further research into the effectiveness of Agile in large scientific projects.

In addition to Agile, an important approach for adaptive management of innovative projects is the RUP methodology, which makes it possible to combine iterative development with clear management of project stages. This is especially relevant for engineering developments that require structured requirements management, risk control, and adaptation to changing conditions.

Thus, the integration of Waterfall, Agile, PMLS, and RUP within the framework of an adaptive project management model makes it possible to take into account the specificity of scientific research and innovative engineering developments.

3. The aim and objectives of the study

The purpose of this study is to build an adaptive project management model based on a combination of Waterfall and Agile methodologies. This will make it possible to improve the efficiency of project management under conditions of changing requirements and deadlines.

To achieve this goal, the following tasks were solved:

– to analyze the problems/complexities of the Waterfall methodology, in particular its lack of flexibility in changing requirements during project implementation and the problems/complexities of the Agile methodology, in particular its lack of clear project deadlines, which is critically important for customers;

– to form an expanded list of project input parameters for the application of Waterfall and Agile methodologies;

– to design the components of an adaptive project management model that combines Waterfall and Agile elements and makes it possible to determine approximate deadlines and take into account changes in requirements during project implementation.

4. The study materials and methods

The object of this study is project management in the field of innovative engineering developments and management of scientific projects under conditions of dynamic requirements, high complexity, and variable implementation deadlines.

The hypothesis of the study assumes that the integration of Waterfall and Agile methodologies into a single adaptive project management model could improve the efficiency of project management under conditions of changing requirements and deadlines, ensuring flexibility without losing a clear organization of processes.

The following assumptions were adopted in the study:

1. It was assumed that under conditions of rapid changes in requirements in the project it is important to have elements of flexibility, as in the Agile methodology, as well as the need to adhere to clear deadlines and a clear structure inherent in Waterfall.

2. It was assumed that the integration of these two methodologies would make it possible to find the optimal balance between flexibility and predictability, which could allow for more effective management of risks and project implementation.

The simplifications concerned the fact that both methodologies could be adapted to each specific project without significant additional costs for retraining personnel or changes in organizational processes.

The study was conducted at Hokord Ltd. [11], a Hong Kong-based engineering innovation company. The company was chosen because it specializes in innovative engineering and has used both Waterfall and Agile project management

methodologies throughout its operations. The company used the Waterfall methodology from 2018 to 2019 and switched to the Agile methodology in 2020.

Based on an analysis of projects implemented by Hokord Ltd., an expanded list of requirements for projects managed using the Waterfall methodology and requirements for projects implemented using the Agile methodology was compiled. This list became the basis for devising an adaptive project management model that combines elements of both methodologies depending on the specificity and needs of a particular project.

The study also applied an algorithm that makes it possible to determine which elements of Waterfall and Agile should be combined in an adaptive model to ensure the effectiveness of project management and at different stages/cycles/sprints of the project. Based on the results, a parametric model was built in which the dependent variable is the adaptive project management model, and the independent variables are a set of parameters selected from the Waterfall and Agile methodologies in accordance with the specificity of the project.

The study is based on the analysis of data on 157 projects of Hokord Ltd. implemented in the period of 2018–2023. To assess the effectiveness of the proposed approach, statistical analysis methods were used that provide an objective comparison of projects implemented using different approaches and help identify optimal combinations of management elements.

5. Results of investigating the adaptive project management model in the field of innovative engineering developments

5. 1. Research on the problems of Waterfall and Agile project management methodologies

Modern project management is characterized by the need to balance predictability and flexibility, especially under conditions of dynamic changes in customer requirements. The two most common methodologies – Waterfall and Agile – offer different approaches to solving this problem. Waterfall provides a clear structure, predictability of deadlines and costs, but suffers from insufficient flexibility. Agile, on the contrary, provides adaptability and interactivity, but loses certainty in planning and control of deadlines. In this context, a hybrid approach, which combines the strengths of both methodologies, becomes an effective tool for managing projects with diverse requirements. Table 1 gives an analysis of the shortcomings of Waterfall and Agile, as well as ways to compensate for them within the framework of a hybrid approach.

Analysis reveals that each methodology has its own strengths, which simultaneously compensate for the limitations of the other. Waterfall provides structure and predictability but is inferior to Agile in the ability to respond to changes and interact with the customer. Agile, in turn, brings flexibility and quick response, but suffers from insufficient clarity of deadlines and limited documentation. A hybrid approach makes it possible to combine these advantages, adapting management to the specificity of each project. Such an approach not only reduces risks and increases efficiency but also helps achieve optimal results under the conditions of a modern dynamic environment.

Table 1

Balance between the disadvantages and advantages of Waterfall and Agile methodologies

Waterfall disadvantage	Compensated in Agile	Agile disadvantage	Compensated in Waterfall
Rigid structure that does not allow for quick adaptation to changes	Flexibility of the iterative approach, which allows for quick adjustments	Lack of clear project deadlines	Rigid planning that provides predictability
Late detection of problems, as testing occurs at the final stages	Continuous testing and feedback throughout the project life cycle	Low level of documentation, which makes scaling difficult	Full documentation provides transparency and control
Unsuitable for dynamic and innovative projects	Ability to respond quickly to changes in customer requirements	Instability of resources due to constant changes in priorities	Resource allocation according to a rigid plan
High risk of losing compliance with customer expectations	Continuous interaction with the customer, which allows for taking into account their feedback	Dependence on active participation of the customer	Fixing requirements at the initial stages minimizes dependencies
Inability to make changes after the stages are completed	A flexible approach allows for adapting the project at any stage	Complexity of managing large, long-term projects	A consistent and structured approach provides control

5. 2. Researching project inputs for Waterfall and Agile methodologies

Project management is a key element of achieving success in any organization. The choice of a project management methodology depends on a number of factors, including the type of project and direction of activity, customer requirements, and the flexibility needed to adapt to change. The two most common project management methodologies (Waterfall and Agile) have their advantages and disadvantages that require a different approach to project inputs (Table 2). Table 2 gives basic project requirements for each of these methodologies, which makes it possible to identify both common and distinctive characteristics of their application.

Table 2 compares project requirements for the Waterfall and Agile methodologies and demonstrates the significant differences between them. Waterfall requires clearly defined requirements and strict planning, which limits flexibility and the ability to adapt to changes during the project implementation process while Agile emphasizes flexibility, constant interaction with the customer and adaptation to changes, which allows for a quick response to new requirements, but can make it difficult to predict deadlines and results. Common requirements, such as the importance of interaction with the customer and the need for risk management, confirm the universality of certain aspects of project management, regardless of the choice of methodology. Each approach is suitable for different types of projects, and their choice depends on the specific conditions and goals of the project.

Table 2

Comparison of project requirements according to Waterfall and Agile methodologies

Project requirement	Waterfall	Agile
Clarity of requirements	All requirements should be clearly defined at the beginning of the project	Requirements may change during the project
Flexibility to change	Little flexibility for changes after the project has started	High flexibility to changes at all stages of the project
Project duration	Fixed deadlines, clearly defined deadlines for each stage	Flexible deadlines that may change depending on needs
Iterativity	No iterativeness, everything happens in stages	Iterative approach, execution through sprints with regular reviews
Interaction with the customer	Limited interaction, mainly at the beginning and end of the project	Continuous interaction with the customer throughout the project
Documentation	Large amount of documentation for each stage of the project	Minimal documentation, focus on functional result
Risk management	Risks are identified at the beginning and controlled throughout the project	Continuous updating of risks during the project implementation process
Performance control	Control of execution according to a predefined plan	Continuous adjustment of plans depending on the current status
Team participation	Clear distribution of roles at each stage of the project	Roles may change depending on tasks and priorities
Predicting results	High predictability of results based on a detailed plan	Low predictability due to adaptive approach

5. 3. Development of the components for an adaptive project management model

As part of building an adaptive project management model, a sequence of actions is proposed for applying individual elements of Waterfall and Agile to project management in the field of engineering developments (Fig. 1).

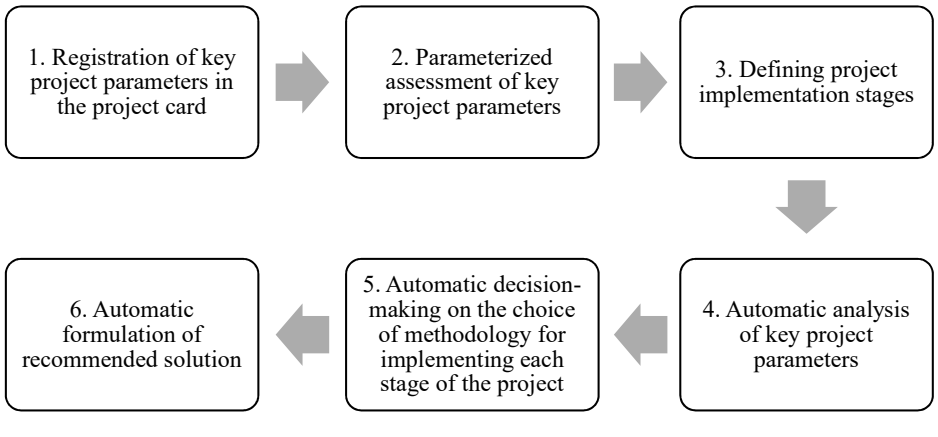

Fig. 1. Sequence of actions for applying individual elements of Waterfall and Agile to project management in the area of engineering developments

Stage 1. At the first stage, the project manager enters project data into the project card. This process includes an assessment of key parameters, such as the type of project, its priority level, variability of requirements, criticality of deadlines, complexity, etc. The data is recorded in a standardized format using electronic forms or a questionnaire, which ensures their further unification. In addition, the main stages of project implementation are determined, including planning, development, testing and support, which makes it possible to clearly outline the project structure. Based on the analysis of data on 157 projects at Hokord Ltd. implemented in the period of 2018–2023, the following project parameters were identified, which form the basis for devising an adaptive model (Table 3).

Table 3

Key parameters of 157 projects implemented at Hokord Ltd.

No.	Parameter	Characteristics
1	Project Type	Determines the industry in which the project is implemented (technological infrastructure, GIS, development of innovative systems and solutions, scientific activities, etc.)
2	Priority	Reflects the importance of the project (high, medium, low)
3	Status	Includes categories such as completed, canceled, in progress
4	Percentage of completion	Indicates how much the project is implemented
5	Duration	Calculated based on the start and end dates of the project
6	Complexity	An indirect parameter that can be derived from the type of project and its status (for example, long-term projects with complex dependencies)
7	Requirements variability	Reflects how often the requirements change (important for Agile)
8	Deadline criticality	Whether the project needs to be completed within a clearly defined timeframe
9	Level of documentation	Indicates the need to create a large amount of documentation
10	Customer involvement	Reflects the level of customer involvement during implementation (high level is important for Agile)
11	Resource availability	Assessment of the stability of available resources
12	Dependences	The presence of other projects or stages that affect the success of implementation

Stage 2. To assess the key project parameters, a set of parameterized project parameter values X is used, each of which corresponds to a certain criterion

$$X = \begin{Bmatrix} x_1, x_2, x_3, x_4, \\ x_5, x_6, x_7, x_8, \\ x_9, x_{10}, x_{11}, x_{12} \end{Bmatrix}, \quad (1)$$

where x_1 is the project type (0 for simple, 1 for complex);

x_2 is the priority (from 1 – very high to 6 – not assessed);

x_3 is the status of the project (1 for completed, 0 for cancelled or in progress);

x_4 is the percentage of completion (from 0 to 100 %);

x_5 is the duration (in days, the difference between the start and end dates);

x_6 is the complexity (0 – low, 1 – high, determined by the type and duration);

x_7 is the variability of requirements (0 – low, 1 – high);

x_8 is the criticality of deadlines (0 – non-critical, 1 – critical);

x_9 is the level of documentation (0 – minimal, 1 – large volume);

x_{10} is the involvement of the customer (0 – low, 1 – high);

x_{11} is the availability of resources (0 – unstable, 1 – stable);

x_{12} – dependences (0 – absent, 1 – present).

The second stage involves normalizing the data in the project card. The collected parameters are converted into a single scale (for example, from 0 to 1) for the purpose of unification for further mathematical analysis. This approach avoids the influence of different scales of variables on the results of the algorithm and ensures the objectivity of the assessments.

Stage 3. Determining the stages of project implementation. The project manager determines the stages of project implementation in agreement with the client. Analysis of the sample of projects allowed me to identify 6 stages of project implementation (Table 4).

Table 4

Stages of implementation of 157 completed projects at Hokord Ltd.

No.	Stage	Characteristics
1	Initiation stage	Implemented using Agile and Waterfall. Business Scenario, Benefit, What is the product, solution or scientific research, Success Criteria
2	Planning stage	Implemented using Waterfall if a large amount of documentation, clear deadlines or stable requirements are required
3	Development stage	Implemented using Agile if adaptability, high level of interaction with the customer and an iterative approach are required
4	Testing stage	Implemented using Waterfall if testing is the final phase; by Agile – if testing is integrated into iterations
5	Support stage	Implemented using Agile if there is a need for constant updates and feedback
6	Completion stage	Implemented using Agile and Waterfall. Project documentation, Archiving, Discussion with teams of all difficulties that arose on the project. Participant remuneration

Stage 4. The fourth stage automatically analyzes key parameters using a regression model implemented in Python. The regression model is based on weight coefficients determined by analyzing previous projects. These coefficients reflect the influence of each parameter on the choice of methodology. For example, the stability of requirements and the volume of required documentation correlate more with the Waterfall methodology, while the variability of requirements and high customer participation contribute to the choice of Agile.

For each stage E_k, belonging to Waterfall (W_k) or Agile (A_k) is determined from the formulas:

$$Wk = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 + \alpha_5 x_5 + \alpha_6 x_6 + \\ + \alpha_7 x_7 + \alpha_8 x_8 + \alpha_9 x_9 + \alpha_{10} x_{10} + \alpha_{11} x_{11} + \alpha_{12} x_{12}, \quad (2)$$

$$Ak = \beta_1 x_4 + \beta_2 x_7 + \beta_3 x_{10} + \beta_4 x_{11} + \beta_5 x_{12}. \quad (3)$$

The coefficients (α, β) reflect the weight of each parameter for the corresponding methodology. I propose determining the values of coefficients α, β using an empirical method based on regression analysis. The independent variable in this case will be the type of project management methodology:

$Y = 0$ (Waterfall),

$Y = 1$ (Agile)).

The multiple regression model for determining the coefficients α, β takes the following form

$$Y = b_0 + b_1 x_1 + b_2 x_2 + ... + b_n x_n + \varepsilon. \quad (4)$$

Stage 5. The fifth stage involves making a decision by the algorithm on the choice of a certain methodology for each stage of the project implementation. Based on the weight coefficients, the values of the functions belonging to the Waterfall and Agile methodologies for each stage are calculated. The decision on the choice of methodology is made according to the rule: if the Waterfall function has a higher value, the stage is implemented using this methodology, otherwise Agile is chosen.

The resulting methodology selection rule (E_k) for the implementation of a specific stage of the project looks as follows:

Methodology (E_k) = {*Waterfall*, if $W_k >= A_k$;

Agile, if $W_k <= A_k$ }. (5)

Stage 6. At the final stage, the algorithm generates recommendations for choosing a methodology for each stage (Table 5). The results are displayed in the form of a report in a pop-up window or an interactive dynamic table of the results panel, which contains recommendations for initiation, planning, development, testing, support, and completion. This allows the project manager to effectively organize the management process, taking into account the specificity of the project and the dynamics of its requirements.

Thus, the adaptive project management model integrates modern approaches to data analysis and decision-making, which ensures increased efficiency of project implementation under complex and changing conditions.

Table 5

Stages in choosing a project implementation methodology

No.	Stage	Key parameters	Formula for choosing between Waterfall and Agile
1	Stage 2: Analysis of input parameters	Project type, requirements variability, deadline criticality, level of documentation	$W_k = \alpha_1 x_1 + \alpha_2 x_2 + \\ + \cdots + \alpha_n x_n,$ $A_k = \beta_1 x_1 + \beta_2 x_2 + \\ + \cdots + \beta_n x_n.$ If $W_k > A_k$, Waterfall is used, otherwise – Agile
2	Stage 4: Evaluation of the effectiveness of each stage	Duration, number of iterations, change control, risks	A regression model is used to determine the most effective approach
3	Stage 5: Selection of an adaptive approach	Generalized estimates of all parameters	Methodology selection based on the weights defined in the regression model

Project analysis algorithm:

1. Collection of input parameters (requirements analysis, flexibility, resources, deadlines).

2. Calculation of indicators of belonging to Waterfall and Agile (using a regression model).

Project classification by methodology:

1. If more than 70% of the parameters correspond to Waterfall, Waterfall is used.

2. If more than 70% of the parameters correspond to Agile, Agile is used.

3. If from 40% to 60% of the parameters correspond to both methodologies, a hybrid approach is used.

4. Adjustment of the approach based on the project stages.

To determine the optimal methodology at different stages (Table 6), a weighting function is used that takes into account the main parameters:

$$Mk = \Sigma \gamma_i x_i, \quad (6)$$

where Mk is the metric for selecting the methodology for stage k, x_i is the project parameters (requirement flexibility, deadline criticality, complexity), γ_i is the weighting factors (determined by the regression model).

If $Mk > 0.5$, Agile is selected, if $Mk < 0.5$ – Waterfall (Table 6).

Table 6

Determining the optimal methodology at different stages

No.	Stage	Methodology at $Mk > 0.5$, Agile	Methodology at $Mk < 0.5$, Waterfall
1	Planning	Flexible approach, minimal documentation	Rigid plan, fixed requirements
2	Development	Iterative process (Scrum)	Clear development stages
3	Testing	Continuous testing (CI/CD)	Final testing after development
4	Support	Regular updates	Clearly regulated maintenance

The optimal project management methodology is determined based on the value of the project flexibility coefficient Mk. If Mk exceeds 0.5, it is advisable to use the Agile approach, which provides adaptability to changes, rapid iterative development, and constant testing. This makes it possible to effectively respond to dynamic requirements and quickly implement updates. On the other hand, when Mk is less than 0.5, it is advisable to use the Waterfall methodology, which involves detailed planning, fixed requirements, and consistent implementation of all stages. This approach guarantees clarity of processes and project controllability, which is critically important for stable environments with minimal changes. Thus, the choice of methodology should correspond to the level of uncertainty and variability of requirements, which makes it possible to achieve the optimal balance between flexibility and predictability of project implementation.

6. Discussion of results based on the development of an adaptive project management model in the field of innovative engineering developments

The results of this study showed that the development of an adaptive project management model that combines Waterfall and Agile makes it possible to eliminate their main limitations (Table 1). The integration of Agile flexibility with Waterfall predictability ensures effective project management under conditions of changing requirements and deadlines. The proposed decision-making algorithm (Fig. 1) allows for the optimal distribution of elements of both methodologies for each stage, which increases stakeholder satisfaction and resource efficiency.

The results of this study confirm the importance of adaptive project management as a strategic approach to overcoming challenges associated with the uncertainty and complexity of modern environments. A number of studies [12–14] emphasize that adaptability is ensured through the integration of review, reflection, and response (RRR) processes, which allows teams to quickly adapt to changes. In particular, paper [12] suggests that such approaches increase project management flexibility and promote stakeholder involvement in decision-making. This is consistent with the findings reported in [13], which suggests that integrating Agile principles, such as iterative cycles and learning, allows for a focus on business value and reduces risk.

The results of study [14] emphasize the role of an integrative approach that combines elements of Waterfall and Agile to improve project management efficiency. It was found that the structured nature of Waterfall planning, combined with the flexibility of Agile iterations, allows for rapid adaptation to changing conditions. These findings are consistent with the results reported in [15], which shows that conventional approaches such as Gantt and critical path do not provide the necessary flexibility in the face of dynamic market changes.

Of interest is study [16], in which the integration of Waterfall and Agile is considered as a strategic approach for adaptive project management. The authors emphasize that such integration improves communication in teams and ensures better compliance of project results with the expectations of stakeholders. This is also confirmed in [1], which emphasizes the importance of team motivation and adaptation of the methodology according to the specificity of projects. However, paper [17] focuses on the general principles of implementing agile methods while my study considers a specific approach to analyzing project stages.

It is important to note that works [18, 19] reveal the importance of adaptive management in the context of innovative projects but do not consider the algorithm and methodology for analyzing projects to make decisions about implementing their stages using the Waterfall or Agile methodology. This study proposed an algorithm based on the assessment of key project parameters, the use of a regression model, and decision-making for each stage. This approach provides the opportunity to combine the advantages of both methodologies depending on the requirements of a specific stage, which is a new aspect compared to existing studies.

Scientific project management has unique challenges associated with a high level of uncertainty, the complexity of predicting results, and the need to integrate interdisciplinary knowledge. Research shows that the use of agile methodologies in scientific projects can significantly improve adaptation to changing conditions.

Thus, an adaptive model of scientific project management should integrate elements of Agile, RUP, and PMLS. This allows for optimal resource management, risk control, and high efficiency of scientific research implementation.

Thus, the proposed model of integration of Waterfall and Agile is not only a response to the need for flexibility but also offers an algorithm based on a systemic approach to decision-making to improve the efficiency of project management.

It is worth noting that the study has certain limitations.

Limited sample: the study was conducted only on the basis of Hokord Ltd., a company engaged in the development

of innovations in the field of vaping and based in Hong Kong. Such a limitation may affect the generalization of the results to other areas of innovative development and location. The results may differ for companies under the influence of sanctions, which may affect the emergence of additional stages of project implementation or changes in key project requirements.

Methodological limitations: it is proposed to use regression analysis to determine parameters α, β. Other methods for analyzing project requirements, such as machine learning (ML) or the use of artificial intelligence (AI) technologies, may provide other weighting factors.

The disadvantage of the study is the assessment of the results on the basis of only one company. This disadvantage can be overcome by increasing the sample of companies studied.

This research may continue by using other technologies for determining the weight coefficients α, β and interpreting key project requirements, such as machine learning (ML) or artificial intelligence (AI) technologies.

7. Conclusions

1. Analysis of the Waterfall and Agile methodologies has revealed that their main shortcomings – the lack of flexibility in Waterfall and the uncertainty of deadlines in Agile – could be mutually compensated within the framework of a hybrid approach. The results demonstrate that the combination of a clear structure and planning of Waterfall with the flexibility and adaptability of Agile makes it possible to achieve a balance between predictability and the ability to quickly respond to changes. The difference of this approach from conventional models is to optimize project management by integrating the best practices of both methodologies, which ensures more effective achievement of project goals. This result is explained by the need to adapt to modern dynamic conditions, where requirements can change during the project implementation process, and customers expect clarity in execution.

2. The expanded list of project input parameters for the application of the Waterfall and Agile methodologies makes it possible to more accurately determine the conditions under which each of the approaches would be most effective. The study showed that Waterfall requires detailed planning and fixed requirements, which provides predictability but limits adaptability to changes. Instead, Agile provides the flexibility of an iterative approach, which makes it possible to quickly adapt to new conditions but makes it difficult to accurately predict deadlines and resources. The difference between the obtained result and known approaches is that it not only details the key parameters of the choice of methodology but also identifies common requirements that can be universal for any project. This is explained by the need for a balanced approach to project management, where the choice between Waterfall and Agile should be based not only on the advantages of each methodology but also on the specificity of the project itself and its variability.

3. The devised components of the adaptive project management model, which combines the elements of Waterfall and Agile, provide a balance between flexibility and predictability. The proposed sequence of actions for applying individual elements of Waterfall and Agile for project management in the field of engineering developments includes the process of collecting and normalizing project data, categorizing the basic parameters and their mathematical analysis using a regression model. This makes it possible to predict project deadlines and adapt the management strategy depending on the variability of requirements, the complexity of the tasks, the level of customer participation, and other factors.

Conflicts of interest

The author declares that he has 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 author confirms that he did not use artificial intelligence technologies when creating the current work.

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