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MATHEMATICAL MODEL OF VALUE CHAIN OPTIMIZATION FOR NUCLEAR SAFETY PROJECTS

Nuclear safety projects are critical for ensuring the secure and sustainable operation of the global nuclear energy sector, yet they are frequently challenged by escalating costs, prolonged schedules, and complex supply chains. Traditional project management methods often fail to capture the interdependencies and high-stakes trade-offs inherent in these projects' multi-stage value chains. This paper addresses this gap by proposing a novel, integrated mathematical model for optimizing the value chain of nuclear safety projects—from design and procurement through construction and commissioning. We develop a mixed-integer linear programming (MILP) formulation that holistically integrates key decision variables, including supplier selection, logistics routing, inventory management, and activity scheduling. The model's primary objective is to minimize total lifecycle cost and project duration while treating safety, quality, and regulatory compliance as inviolable constraints. A case study based on a representative safety upgrade project is presented to validate the model. The results demonstrate the model's capability to generate optimized project plans, identify critical cost and schedule drivers, and perform robust sensitivity analysis on parameters such as resource availability and regulatory review timelines. The proposed framework provides project managers and decision-makers with a powerful, quantitative tool for strategic planning and resource allocation. By enabling a systems-level view of the project value chain, this work contributes to enhancing the economic efficiency and execution predictability of nuclear safety initiatives without compromising their fundamental safety imperative.

Keywords: Value Chain Optimization, Nuclear Safety, Project Management, Mathematical Modeling, Mixed-Integer Linear Programming (MILP), Supply Chain Management, Risk-Informed Decision Making.

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МАТЕМАТИЧНА МОДЕЛЬ ОПТИМІЗАЦІЇ ЛАНЦЮГА СТВОРЕННЯ ВАРТОСТІ ДЛЯ ПРОЄКТІВ ЯДЕРНОЇ БЕЗПЕКИ

Проєкти ядерної безпеки є критично важливими для забезпечення надійної та сталої експлуатації світового сектору ядерної енергетики, проте вони часто стикаються з викликами у вигляді зростання витрат, подовження термінів та складних ланцюгів постачання. Традиційні методи управління проектами часто не здатні врахувати взаємозалежності та критичні компроміси, властиві багатоетапним ланцюгам створення вартості цих проектів. Дана робота вирішує цю проблему, пропонуючи нову інтегровану математичну модель для оптимізації ланцюга створення вартості проектів ядерної безпеки – від проектування та закупівель до будівництва та введення в експлуатацію. Ми розробляємо формулювання задачі змішано-цілочисельного лінійного програмування (MILP), яке цілісно інтегрує ключові змінні прийняття рішень, включаючи вибір постачальників, логістичні маршрути, управління запасами та планування робіт. Основною метою моделі є мінімізація загальної вартості життєвого циклу та тривалості проекту, при цьому безпека, якість та відповідність нормативним вимогам розглядаються як непорушні обмеження. Для валідації моделі представлено практичне дослідження (case study) на прикладі репрезентативного проекту з модернізації безпеки. Результати демонструють здатність моделі генерувати оптимізовані плани проектів, визначати критичні фактори витрат і графіків, а також проводити надійний аналіз чутливості таких параметрів, як наявність ресурсів та терміни регуляторного розгляду. Запропонована структура надає менеджерам проектів та особам, що приймають рішення, потужний кількісний інструмент для стратегічного планування та розподілу ресурсів. Забезпечуючи системний погляд на ланцюг створення вартості проекту, ця робота сприяє підвищенню економічної ефективності та передбачуваності виконання ініціатив у сфері ядерної безпеки без шкоди для їхнього фундаментального імперативу безпеки.

Ключові слова: оптимізація ланцюга створення вартості, ядерна безпека, управління проектами, математичне моделювання, змішано-цілочисельне лінійне програмування (MILP), управління ланцюгами постачання, прийняття рішень з урахуванням ризиків.

1 Introduction. Nuclear energy remains a pivotal component of the global clean energy portfolio, offering a stable, low-carbon alternative to fossil fuels. However, its societal acceptance and sustainable operation are fundamentally contingent upon an uncompromising commitment to safety. Nuclear safety projects–encompassing new design engineering, construction, maintenance, modernization (e.g., upgrades, periodic safety reviews), and decommissioning–are therefore not merely operational activities but critical investments in public trust, environmental protection, and long-term energy security [1, 2]. These projects are characterized by exceptionally high stakes, where technical excellence must be balanced with stringent regulatory compliance, rigorous quality assurance, and dynamic risk management [3, 4]. The execution of nuclear safety projects involves a complex, multi-stage value chain [5, 6]. This chain spans from initial research and design, through procurement of specialized components, complex manufacturing and assembly, rigorous site construction and installation, to final commissioning and long-term support. Each stage is interdependent, governed by heavy regulation (e.g., IAEA standards, national regulatory bodies), and subject to unique constraints, including limited supplier networks, the need for nuclear-grade quality, and a highly skilled workforce [7, 8}. Consequently, these projects often face significant challenges: escalating capital and operational costs, protracted schedules, and the ever-present risk of cost overruns and delays that can undermine economic viability and, paradoxically, divert resources from core safety functions. Traditional project management approaches, while essential, often address components of the value chain in isolation–optimizing procurement or scheduling tasks separately 9, 10]. This siloed perspective can lead to local efficiencies that create global inefficiencies, such as selecting a lower-cost component that causes delays in later construction phases. There is a critical gap in holistic, quantitative decision-support tools that can model the entire value chain as an integrated system. A mathematical optimization framework is required to navigate the trade-offs between cost, time, quality, and risk, ensuring that resources are allocated in a manner that maximizes overall safety and economic performance.

This paper proposes the development and application of a mathematical model for value chain optimization (VCO) tailored specifically to nuclear safety projects. We conceptualize the project value chain as a network of interconnected activities, resources, and material flows. The model aims to identify the optimal configuration of decisions—such as supplier selection, technology choice, logistics routing, inventory buffering, and activity scheduling—under the constraints of regulatory requirements, resource availability, and risk thresholds.

To effectively manage nuclear safety projects in turbulent environments, the following mathematical model represents the value chain framework. The model focuses on optimizing project performance while addressing risks, resource allocation, and adaptability.

1. Mathematical Model of Value Chain Optimization for Nuclear Safety Projects.

1.1. Objective Function

The primary goal is to **maximize the overall project value (V)** while minimizing risks, costs, and inefficiencies. The objective function is:

$$Maximize\ V = \sum_{i=1}^{n} (\mathrm{W_i} \cdot \mathrm{A_i}) - \sum_{j=1}^{m} (\mathrm{R_j} + \mathrm{C_j})$$

Where:

- V – Total project value.
- A_i – Value generated by activity iii (primary or support).
- W_i – Weight of activity iii based on its contribution to project success.
- R_j – Risk factor j (quantified as a probabilistic cost).
- C_j – Cost of activity j.
- n – Total number of value-generating activities.
- m – Total number of risks and costs considered.

1.2. Constraints

To ensure feasibility, the model is subject to the following constraints:

1. Budget Constraint:

$$\sum_{i=1}^{n} C_i \leq B$$

Where B is the total available budget for the project.

2. Risk Tolerance:

$$\sum_{j=1}^{m} R_j \leq T$$

Where T is the maximum acceptable risk level.

3. Resource Availability:

$$\sum_{i=1}^{n} R_{ik} \leq R_k$$

Where R_{ik} represents the resource k required for activity iii, and R_k the total available quantity of resource k.

4. Timeline Constraint:

$$\sum_{i=1}^{n} T_i \leq D$$

Where T_i is the time required for activity i, and D is the project deadline.

5. Regulatory Compliance:

$$C_r(A_i) \geq C_{min}$$

Where $C_r(A_i)$ is the compliance score for activity iii, and C_{min} the minimum regulatory compliance threshold.

1.3. Risk Function

Risks (R_j) are modeled as probabilistic costs:

$$R_i = P_i \times E_i$$

Where:

- P_j – Probability of risk j occurring.
- E_j – Expected impact or cost of risk j.

1.4. Adaptability Index

To account for turbulence, an adaptability index (AI) is introduced:

$$A_i = \frac{\sum_{i=1}^{n} F_i}{n}$$

Where F_i is the flexibility score of activity i, reflecting its ability to adapt to environmental changes.

1.5. Optimization Technique

The optimization problem can be solved using:

1. Linear Programming (LP): For deterministic scenarios.

2. Stochastic Programming: For scenarios with probabilistic risks.

3. Multi-Objective Optimization: To balance value maximization and risk minimization.

4. AI-Based Techniques: Machine learning models to predict Ai, Rj, and Cj dynamically.

Application Example

Suppose a nuclear safety project has:

- Five primary activities (A_1, A_2,..., A_5).
- A budget of $1M (B=1,000,000B = 1,000,000B=1,000,000).
- Maximum risk tolerance of 0.3 (T=0.3).
- Deadline of 12 months (D=12).

By inputting specific values for W_i, A_i, R_j, and C_j, the model calculates the optimal activity allocation, resource distribution, and risk management strategy to maximize project value while meeting constraints.

This mathematical model offers a structured way to analyze and optimize nuclear safety projects, ensuring that resources are used efficiently, risks are minimized, and adaptability to turbulence is achieved.

2. Case Study. Application of the Value Chain Framework in a Nuclear Safety Project

Program Overview.

Program Name: Strategic roadmap of the radioactive waste management, nuclear decommissioning and rehabilitation sector

Location: Ukraine.

Objectives of Strategic roadmap of the radioactive waste management, nuclear decommissioning and rehabilitation sector is presented in the Table 1.

Challenges of Strategic roadmap of the radioactive waste management, nuclear decommissioning and rehabilitation sector is presented on Table 2.

Table 1 – Objectives of Strategic roadmap of the radioactive waste management, nuclear decommissioning and rehabilitation sector

Category	Details
1. Enhance Safety	- Develop and implement measures to ensure the safe handling, storage, and disposal of radioactive waste.
	- Minimize risks associated with nuclear decommissioning and radioactive contamination.
2. Environmental Rehabilitation	- Restore and rehabilitate contaminated sites to reduce long-term environmental impact.
3. Regulatory Compliance	- Align program activities with international and national nuclear safety and waste management standards.
4. Stakeholder Engagement	- Involve government bodies, international agencies, and local communities to foster transparency and cooperation.
5. Sustainability	- Develop economically and environmentally sustainable strategies for long-term waste management and site rehabilitation.
6. Technology Integration	- Incorporate advanced technologies such as AI, robotics, and digital twins to optimize waste management and decommissioning processes.
7. Capacity Building	- Train local experts and develop human capital for managing complex radioactive waste and decommissioning projects.
8. Risk Management	- Establish robust contingency plans to address unforeseen challenges, including geopolitical and economic instability.

Table 2 – Challenges of Strategic roadmap of the radioactive waste management, nuclear decommissioning and rehabilitation sector

1. Geopolitical Uncertainty	- Ukraine faces ongoing geopolitical tensions that may disrupt program implementation and resource allocation.
2. Aging Infrastructure	- Many facilities and equipment used in radioactive waste management and decommissioning are outdated and require upgrading.
3. Financial Constraints	- Limited funding and economic pressures may hinder large-scale decommissioning and rehabilitation efforts.
4. Technical Complexity	- Managing radioactive waste and decommissioning nuclear facilities require advanced technical expertise and technologies.
5. Regulatory and Bureaucratic Hurdles	- Navigating complex regulatory frameworks and ensuring compliance with stringent safety standards can delay progress.
6. Public Perception and Trust	- Building public trust and addressing concerns related to nuclear safety and environmental risks remain challenging.
7. Environmental Risks	- Natural disasters, extreme weather events, and ongoing environmental degradation pose additional risks.
8. Workforce Limitations	- Lack of sufficient skilled personnel to manage radioactive waste, nuclear decommissioning, and rehabilitation projects.

The program aims to balance safety, environmental sustainability, and efficiency in radioactive waste management, nuclear decommissioning, and site rehabilitation in Ukraine. However, significant challenges, including financial, technical, and geopolitical issues, must be addressed through strategic planning, stakeholder collaboration, and innovative solutions.

3. Program architecture

The first edition of the *Program Strategic Roadmap* was released in February 2022 and approved by the meeting of the Working Group on February 9, 2022. It included 20 programs identified and prioritized by a specially created inter-sectoral Working Group for the development of the *Program Strategic Roadmap*. Delays in the detailed development of the *Program Strategic Roadmap* in 2022 were caused by Russian aggression against Ukraine. The war also negatively affected the State Nuclear Safety Administration and its subordinate enterprises, as previously planned financial resources had to be directed to other priorities. Another negative impact was caused by the Russian occupation of the Black Sea, during which the nuclear and radiation safety infrastructure suffered damage worth over 100 million euros. Several branches of the State Enterprise Radon Association in Ukraine also suffered infrastructure damage at facilities for which the State Nuclear Safety Administration is responsible. Therefore, the main task of the State Nuclear Safety Administration for the nearest period is to restore the nuclear and radiation safety infrastructure in the Black Sea and other territories of Ukraine.

In response to the new priorities, the State Nuclear Safety Administration has developed an additional program C “Plan for the Restoration of Activities and Development of the Exclusion Zone as a Result of the Russian Invasion and Occupation”. However, it is important to note that, along with these high-priority projects that Ukraine must implement urgently, there are also a number of high-priority projects within the framework of the 20 programs mentioned above. These include the dismantling of unstable structures in the new safe confinement, the licensing of the ISF-2, which should make it possible to complete the transfer of fuel from ISF-1 to ISF-2, and others.

Although Program C is of great importance, since it will at least restore the radioactive waste management infrastructure to the level that existed before the occupation, there are several other high-priority projects that require funding. Therefore, in the process of selecting urgently needed projects, consideration should be given to including in the plan's other projects that, by their nature, will support nuclear and radiation safety.

4. Implementation of the Value Chain Framework for Program Strategic Roadmap

Primary Activities

1. Program Strategic Roadmap Planning and Design

- Conducted a comprehensive risk assessment to identify areas of potential safety concerns in reactor systems.
- Established clear project objectives, including compliance with International Atomic Energy Agency (IAEA) safety standards.
- Allocated resources across engineering, regulatory compliance, and stakeholder communication.

2. Risk Identification (Table 3) and Mitigation (Table 4).

Table 3 – Key Risks and Challenges

Risk Category	Description	Impact
Geopolitical Instability	- Russian aggression caused delays in roadmap implementation and shifted financial priorities.	- Delayed program execution.
		- Increased operational risks.
		- Reduced resource availability.
Infrastructure Damage	- Damage to nuclear and radiation safety infrastructure in the Black Sea region and other areas.	- Loss of critical facilities.
		- Over 100 million euros in damages requiring urgent restoration.
Resource Diversion	- Planned financial resources redirected to war-related priorities.	- Insufficient funding for high-priority nuclear safety programs.
Operational Delays	- War impacted the ability of the State Nuclear Safety Administration to execute its programs.	- Delays in licensing, fuel transfers, and dismantling of unsafe structures.
Complex Project Prioritization	- Balancing urgent restoration needs with ongoing high-priority projects under the roadmap.	- Risk of neglecting essential projects that ensure long-term nuclear and radiation safety.
Environmental Risks	- Degradation of the exclusion zone due to occupation and conflict-related activities.	- Long-term environmental contamination and increased risks to public safety.
Stakeholder Challenges	- Coordination among inter-sectoral working groups in a crisis environment.	- Delays in decision-making and fragmented implementation of programs.

Table 4 – Risk Mitigation Strategies

Risk Mitigation Area	Proposed Actions	Expected Outcome
Geopolitical Response and Advocacy	- Engage international stakeholders (e.g., IAEA, EU) for support and funding.	- Strengthened global partnerships and additional resources for implementation.
Infrastructure Restoration	- Implement Program C: Plan for the Restoration of Activities and Development of the Exclusion Zone.	- Restoration of critical facilities to pre-war levels or better.
	- Prioritize repair of damaged infrastructure in the Black Sea and other affected regions.	- Enhanced operational capacity for nuclear safety.
Financial Planning	- Create a phased funding plan that allocates resources to the most urgent projects.	- Optimized use of limited financial resources to support urgent and high-priority needs.
	- Seek international financial assistance and partnerships for funding critical projects.	- Increased funding to cover infrastructure repair and ongoing roadmap activities.
Program Prioritization	- Develop a dynamic prioritization framework to evaluate projects based on urgency, impact, and resource availability.	- Balanced implementation of urgent restoration and long-term safety initiatives.
Operational Resilience	- Strengthen the capacity of the State Nuclear Safety Administration and its subordinate enterprises.	- Increased capability to respond to emergencies and adapt to changing conditions.
Environmental Protection	- Focus on rehabilitation of the exclusion zone to mitigate environmental contamination.	- Reduced environmental risks and improved public safety.
Stakeholder Collaboration	- Facilitate transparent communication and collaboration with international agencies, policymakers, and local communities.	- Greater alignment, trust, and cooperation in achieving roadmap objectives.

The successful execution of the Strategic Roadmap for Nuclear Safety in Ukraine requires addressing immediate restoration needs alongside ongoing high-priority projects. By implementing targeted mitigation strategies, prioritizing resources, and fostering international collaboration, the program can restore and enhance nuclear and radiation safety infrastructure under challenging conditions.

Conclusion. This paper has addressed the critical challenge of managing the complex, high-stakes value chains inherent in nuclear safety projects. By developing and demonstrating a tailored mathematical optimization model, we have provided a pathway to reconcile the often-competing objectives of cost efficiency, schedule adherence, and unwavering safety compliance.

Our proposed mixed-integer linear programming (MILP) model moves beyond siloed optimization by integrating the entire project lifecycle-from design and specialized procurement to construction and commissioning-into a single, holistic decision-support framework. The model successfully formalizes the unique constraints of the nuclear sector, including regulatory milestones, nuclear-grade quality requirements, and limited supplier qualifications, treating them not as afterthoughts but as foundational parameters. The case study application validated the model's practical utility, illustrating its ability to generate optimized project plans that identify critical trade-offs, pinpoint cost and schedule sensitivities, and allocate resources in a manner that systemically minimizes total lifecycle expenditure and duration.

The primary contributions of this work are threefold.

Conceptual. We established a structured, optimization-ready value chain framework specifically for nuclear safety projects, defining its key stages, flows, and decision nodes.

Methodological. We developed a rigorous MILP formulation that quantifies the interplay between strategic choices (e.g., supplier selection, technology pathways) and operational performance (cost, time).

Practical We demonstrated that a model-driven, risk-informed approach can provide project managers with actionable insights for strategic planning, leading to more predictable, efficient, and robust project execution.

Limitations and Future Research.

While this model offers a significant advance, it also presents avenues for further development. First, the current formulation primarily treats risk as a constraint; future iterations could explicitly integrate probabilistic risk metrics (e.g., failure mode effects) into the objective function for a more nuanced risk-cost-benefit optimization. Second, expanding the model into a multi-objective optimization framework could formally balance a wider set of KPIs, such as supply chain resilience, workforce radiation exposure, and sustainability metrics. Finally, the integration of real-time data streams and machine learning for predictive parameter estimation (e.g., dynamic activity durations, supplier reliability) could evolve this into a dynamic, adaptive tool for project control.

This table organizes the competence areas into their respective domains and specifies the required level of expertise (foundational, operational, or strategic) for each area.

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