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A REVIEW OF THE CURRENT STATE OF RESEARCH IN QUALITY ASSURANCE IN THE NUCLEAR INDUSTRY

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Abstract: *This paper reviews quality assurance and supplier evaluation in the nuclear industry, with particular attention to the shift from traditional audit-based approaches toward technology-enabled methods. Drawing on the literature, it examines how artificial intelligence, digital twins, blockchain, and the Industrial Internet of Things (IIoT) may improve traceability, automation, and predictive analytics. The review indicates that current practice remains limited by fragmented implementation, the absence of integrated frameworks, and barriers to adoption within stringent regulatory environments. In response, the paper identifies priorities for future research, including risk-based supplier assessment, integration of digital technologies, and the development of unified evaluation models. It also introduces 3D-Q (Data-Driven, Defense-in-Depth Quality) as a proposed framework for moving quality assurance from reactive defect detection toward proactive defect prevention through real-time monitoring, predictive analytics, and enhanced traceability. Overall, the review suggests that more integrated and interdisciplinary approaches are needed to improve efficiency, reduce risk, and strengthen the safety and reliability of nuclear supply chains.*

Key words: *Nuclear industry, Quality assurance, Supplier evaluation, Risk management, Artificial intelligence, Digital Twin, Blockchain, IIoT, Traceability, Predictive analytics, Supply chain*.

1. INTRODUCTION

Quality assurance in the nuclear industry is shaped by stringent safety expectations and dense regulatory oversight. As nuclear facilities are expanded, modernized, and maintained over long operating lifetimes, assurance activities must extend beyond internal processes to the control of increasingly complex supply chains [1, 2].

In general, quality assurance comprises planned and systematic activities intended to provide confidence that products, services, and processes meet specified requirements. In the nuclear sector, these activities span the full facility life cycle, including design, manufacturing, operation, maintenance, and decommissioning. Quality assurance therefore functions not merely as final product verification, but as continuous control over how processes are performed and documented [1, 3].

A central element of any nuclear quality assurance system is traceability, understood as the ability to identify the origin, history, and use of materials, components, and processes. In this context, traceability is essential because it enables the assessment of non-conformities, supports timely corrective action, and reduces the risk that defects remain undetected across the facility life cycle [3, 4].

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The evolution of nuclear quality assurance has been driven by the need for strict control, extensive documentation, and formalized accountability, as reflected in standards and guidance issued by international and national authorities. In particular, the IAEA, ASME standards, and national regulatory bodies define expectations for quality management systems, document control, traceability, non-conformity management, and supplier evaluation [1, 2].

Within this framework, the supply chain becomes a critical site of quality assurance rather than a peripheral administrative function. Non-compliance in supplied materials, components, or services can directly affect safety-related systems; accordingly, supplier selection, qualification, evaluation, and monitoring must be conducted against explicit technical and quality criteria consistent with nuclear regulatory requirements [4, 5].

Recent technological developments have introduced new approaches to quality assurance, including digitization, artificial intelligence (*Artificial Intelligence* – AI) [5, 6], and advanced analytical methods. Although these approaches may improve efficiency and oversight, their practical integration into regulated nuclear quality systems remains uneven and raises implementation challenges.

Against this background, a key problem is not the absence of quality assurance requirements, but the difficulty of ensuring consistent traceability and effective supplier oversight across the nuclear supply chain. This gap can weaken the early detection of non-conformities, complicate corrective action, and increase operational and regulatory risk. Accordingly, this chapter reviews the current state of research on quality assurance and supplier auditing in the nuclear industry in order to identify the main research directions, the methods used, and the limitations that define the basis for the present study.

The analysis carried out in the present scientific report aims to investigate current regulations and research in the field of quality assurance and supplier auditing in the nuclear industry. The analysis investigates international standards, reports of nuclear energy organizations and scientific contributions related to quality management, risk management and supplier evaluation of nuclear-specific components and services.

At the same time, the report aims to highlight the applicability of modern and innovative technologies, based on digitization, artificial intelligence and advanced analysis and modeling methods, in quality assurance processes. Based on the literature analyzed, critical and comparative analyzes are carried out to identify the main contributions, limitations and gaps existing in the field, thus constituting the foundation for defining the preliminary directions of doctoral research.

2. REGULATORY FRAMEWORK AND STANDARDIZATION

The normative framework and standardization are core elements of quality assurance in the nuclear industry, establishing technical, organizational, and safety requirements across the life cycle of nuclear installations. The sector is more heavily regulated than many other industries because failures can have severe safety and environmental consequences.

At the international level, the IAEA plays a central role by developing standards and guidance on management systems, quality assurance, and the evaluation of nuclear suppliers. Documents such as the IAEA *Safety Standards Series* and G.S.R. *Part* 2 [7] specify requirements for safety management, safety culture, documentation control, and the traceability of processes and components used in nuclear facilities.

În mod similar, standardul ISO 19443:2018 [8] represents an important benchmark for quality management in the nuclear supply chain. It is based on ISO 9001 principles and adapted to the specific requirements of the nuclear industry. This standard introduces additional requirements for nuclear safety, counterfeit product prevention, and supplier control, with the objective of increasing the level of reliability and traceability within the supply chain.

In parallel, the standards developed by *American Society of Mechanical Engineers* (ASME), such as ASME NQA-1 and ASME codes *Section* III [1], define detailed requirements concerning design, manufacture, testing and quality control of components used in nuclear installations. These standards are widely used in the nuclear industry and form the basis for the implementation of quality assurance programmes in numerous nuclear organizations and projects.

At the national level, regulatory authorities, such as the National Commission for the Control of Nuclear Activities (CNCAN) [9] în România or *Nuclear Regulatory Commission* (NRC) in the United States of America, have the role of implementing and monitoring compliance with regulatory requirements applicable to the nuclear field. These regulatory bodies establish requirements for the authorization, conformity assessment and supervision of activities with an impact on nuclear safety.

An important aspect of the regulatory framework is the differentiation between components with a role in nuclear safety (*Safety-Related*) and commercial products used in nuclear applications, a process known as *Commercial Grade Dedication* (CGD) [2, 10]. This process involves the evaluation and qualification of commercial products for use in systems with a nuclear safety role, in order to ensure compliance with technical and safety requirements specific to the nuclear field.

The authority flows from government to standards, while contracts can enforce compliance at different levels as follows [11]:

- At the top are laws, decrees, and orders issued by the government, representing the highest level of legally binding authority.
- Below them are regulations, licences, and authorizations developed by regulatory bodies, which provide more specific and enforceable rules.
- The next level consists of regulatory guidance, which is generally not legally binding but helps interpret and apply regulations.
- At the base, there are standards created by standards development organizations; these are typically voluntary unless made mandatory by regulations or contracts.

3. GENERAL ASPECTS OF SUPPLIER EVALUATION AND MONITORING IN THE NUCLEAR INDUSTRY

3.1. Supplier quality management: current models and strategies

Supplier assessment and monitoring are core elements of quality assurance in the nuclear industry because they directly affect facility safety and reliability. Because supplied products and services are integrated into critical systems, supplier selection and control must comply with stringent quality and regulatory requirements [9, 10].

Supplier evaluation requires analysis of multiple criteria, including technical capability, industry experience, past performance, quality management systems, and compliance with applicable standards. In practice, evaluation extends beyond initial selection and continues throughout the relationship through monitoring and periodic re-evaluation to sustain performance and reduce supply-chain risk [5].

Vendor monitoring is carried out through a number of specific tools, such as audits, inspections, checkpoints and documentary checks. These activities allow the identification of possible non-conformities and the assessment of how suppliers comply with technical and regulatory requirements. Depending on the level of risk associated with the products provided, the intensity of these activities may vary, requiring a differentiated approach based on the assessment of the risks associated with the products and services provided [4, 5].

An essential element is ensuring the traceability of products and processes, which supports the identification of the origin of components and the assessment of their impact on the systems in which they are used. In the context of complex supply chains, traceability becomes a critical element for preventing the use of non-compliant or counterfeit products and for reducing the risks associated with the supply chain [9, 10].

In addition, the analyzed sources highlight a number of challenges associated with the supplier evaluation process, such as the diversity of requirements imposed by different standards, the existence of multiple audits applied to the same suppliers and the difficulty of ensuring effective monitoring of extended supply chains. These aspects can lead to redundancies and inefficient use of resources, highlighting the need to optimize the evaluation and monitoring processes of suppliers [5].

Therefore, the need to use effective and integrated methods of evaluation and monitoring of suppliers is outlined, which allow the correlation of information from audits, inspections and evaluations and contribute to reducing risks and improving the performance of quality assurance processes [4, 5].

3.2. Risks and challenges in the supply chain

A recurring concern in the literature is the risk posed by counterfeit, fraudulent, or suspect components, referred to as *Counterfeit, Fraudulent and Suspect Items* (CFSIGNS) [10]. Their entry into the supply chain can compromise the safety and reliability of nuclear installations, particularly in systems with a nuclear security function. Supplier evaluation must therefore include robust mechanisms for verifying product traceability and conformity.

The nuclear industry also faces pressures from a shrinking industrial base and the difficulty of identifying qualified suppliers [11, 14], especially after prolonged stagnation or during rapid technological change. These conditions reinforce the need for qualification and monitoring strategies that can maintain the quality and safety levels required by nuclear regulation.

Knowledge management [15] is likewise central to quality assurance because expertise must be transferred to new generations of specialists and suppliers. Loss of accumulated nuclear-sector experience can hinder the implementation and maintenance of quality requirements, which underscores the need for effective mechanisms for knowledge retention and transfer across organizations and supply chains.

4. MODERN AND INNOVATIVE METHODS AND TECHNOLOGIES USED IN QUALITY ASSURANCE IN THE NUCLEAR INDUSTRY

The technological evolution of recent years has led to the development and integration of modern methods in the quality assurance processes of the nuclear industry, contributing to the increase of efficiency, the level of automation and the ability to analyze data. These technologies allow the improvement of evaluation, monitoring and control processes of suppliers, as well as the optimization of inspection and audit activities, being supported by the integration of digital solutions, of AI and digital twin technologies – *Digital Twin* [5, 6, 14].

4.1. Artificial Intelligence and Machine Learning

One of the most significant areas of development is the application of artificial intelligence and, more specifically, machine learning (ML). Recent studies indicate that ML can support defect detection, analysis of images generated by non-destructive testing, and risk assessment for critical systems. ML-based methods can also optimize inspection processes through risk-informed approaches, thereby reducing costs and improving the efficiency of control activities [2, 5, 15]

The integration of modern technologies into quality assurance processes can be conceptually represented by a model that highlights the transition from traditional methods to approaches based on advanced analysis and digitization, as illustrated in Fig. 1.

As can be seen, the integrated model offers the possibility of correlating information from audits and inspections with data generated by modern technologies, facilitating the transition from a reactive to a proactive approach in quality assurance processes.

The responsibilities of participants in the nuclear-industry component chain can be represented through the flow of documentation recorded on the blockchain [20]:

4.2. Digital Twin

In parallel, the concept of the digital twin has gained increasing attention in the nuclear industry because it enables real-time modelling and simulation of systems and processes. This technology supports continuous monitoring of equipment performance, anticipation of potential failures, and optimization of maintenance activities, thereby improving installation reliability and strengthening quality assurance processes [16]. A digital twin is a virtual replica of a physical system. Its main technological components include the Internet of Things (IoT), cloud computing, sensors, web-based data infrastructure, artificial intelligence (AI), simulation and emulation, and data visualisation [16].

4.3. Blockchain

Another area of interest is the use of blockchain technologies to ensure traceability in the supply chain. Recent studies show that blockchain-based systems can increase transparency, prevent the introduction of counterfeit products, and improve control over the flow of materials and components, with direct implications for the safety and efficiency of quality assurance processes [18, 19].

Several blockchain features are relevant to the nuclear-industry component supply chain [20]. The database is immutable and can preserve product-specific life-cycle records, which improves transparency and reduces risks associated with data manipulation. The concept also incorporates smart contracts and restricts access, monitoring, and verification functions to authorized entities. In this context, blockchain can support a more transparent, accountable, and secure approach to component management in the nuclear industry.

The responsibilities of participants in the nuclear-industry component chain can be represented through the flow of documentation recorded on the blockchain [20]:

- Manufacturer – Add Observer, Add Sourece, Transfer Source, Update Source, View Source Details;
- User – Transfer Source, Update Source, View Source Details,

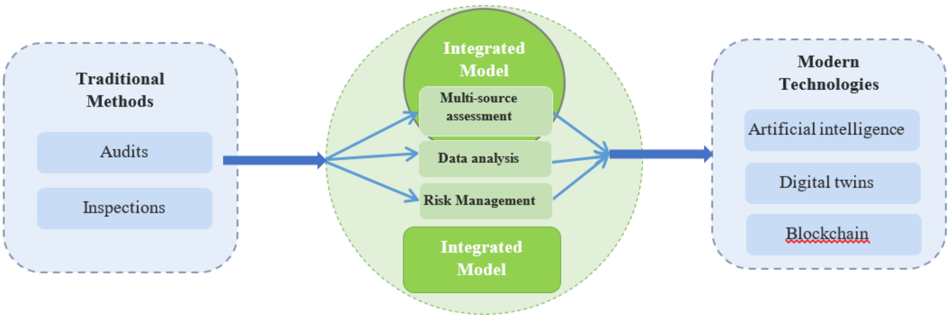

Fig. 1. The evolution from traditional methods to modern technologies in supplier evaluation and monitoring.

- Observer – View Source Details,
- Administrator – Add Manufacturer.

Reference [17] examines in detail the role of blockchain in the component supply chain, including the relationships among key actors such as suppliers, manufacturers, distributors, and final beneficiaries.

4.4. Industrial Internet of Things (IIoT) and real-time monitoring

In addition, the development of the Industrial Internet of Things (IIoT) and industrial communication networks enables the real-time collection and transmission of data, facilitating continuous process monitoring and the integration of information from multiple sources. These technologies support higher levels of automation and improve decision-making within quality assurance systems [21, 22].

Some quantifiable elements can give an overview of the IIoT concept [21, 22]:

- autonomous vehicles and mobile robotic platforms;
- remotely controlled machinery;
- analysis and monitoring of data from sensors;
- worker safety and protection against hazards;
- unloading tasks;
- portable industrial systems and augmented reality.

4.5. Non-destructive testing (NDT)

In the field of quality control, non-destructive testing methods – *Non-Destructive Testing* (NDT) – have experienced significant development through the integration of advanced analysis technologies and evaluation. These methods allow the identification of defects without affecting the integrity of the products, being essential to ensure the conformity of the components used in the nuclear industry and to increase the efficiency of the inspection and quality control processes [17, 23, 24].

Overall, the work consulted underlines that the integration of modern technologies into quality assurance processes contributes to increasing efficiency, reducing risks and improving systems performance. However, their implementation is still limited by the complexity of the processes, the difficulty of integration into existing systems and the need to adapt to the strict requirements of the nuclear industry, the, aspects that highlight the need to develop integrated analysis and optimization models [6, 16, 17, 23].

5. CRITICAL AND COMPARATIVE ANALYSIS OF METHODS AND TECHNOLOGIES USED IN QUALITY ASSURANCE

Given the increasing diversity of quality-assurance methods and technologies in the nuclear industry, a comparative analysis is needed across regulatory, standardization, and implementation dimensions to clarify their respective advantages, limitations, and appropriate contexts of use. The reviewed literature spans approaches ranging from traditional audits and inspections to technologies such as AI, *Digital Twin*, *blockchain*, and IIoT, which differ substantially in maturity, integration, and practical applicability within existing systems [5, 14, 15].

The result of the bibliographic research based on the specified criteria is the relevant information presented in Table 1, which allows for a comparative analysis of the main approaches identified in the specialized literature. The bibliographic sources treated are grouped by categories of interest in terms of both traditional methods, based on audits and inspections, as well as modern technologies oriented towards digitization, automation and predictive analysis, highlighting current areas of application, limitations and directions of development. Two sections are also presented that refer to standards and regulations, to documents and reports provided by bodies in the field, as well as to traditional audits and inspections.

The comparative analysis of the methods and technologies highlighted in Table 1 shows a clear evolution from traditional approaches, based on audits and inspections, towards modern methods, oriented towards digitization, automation and predictive analysis.

Tabel 1

Comparative analysis of methods and technologies used in quality assurance in the nuclear industry

Method / Technology	Description	Advantages	Limitations	Scope	Reference
Standards and International Regulations	International Standard for quality management in the nuclear supply chain, based on the principles of	Increased traceability, standardising processes and	- complex implementation and - the need to adapt systems existing	Quality management and Evaluation of suppliers in the	ISO 19443:2018/Amd 1:2024 [8, p. 19443]

	ISO 9001 and adapted to the specific requirements nuclear industry	improving control suppliers		nuclear industry	
	Amendment of ISO 19443 standard on clarifying and updating the requirements applicable to Quality Management in the Nuclear Industry	Improvement compliance and updating of the requirements for Nuclear supply chain	- requires continuous adaptation of organizational processes and - staff training	Quality Management Systems and supplier control in the nuclear industry	ISO 19443:2018/Amd 1:2024 [8]
	International Standard on safety management and quality assurance in Nuclear installations	It provides a unified framework for Safety management and nuclear safety culture	- Complex application and - the need to adapt to the national and organisational regula-tions	Safety management and Quality assurance in the nuclear industry	IAEA Safety Standards Series No. GSR Part 2, 2016 [7]
	Management and Control Guide supply chain and supplier assessment in the nuclear power	Improvement traceability and control of suppliers in the processes of Supply	- requires the implementation of processes monitoring and documentation	Supply Chain Management and supplier assessment in the nuclear industry	IAEA Nuclear Energy Series No. NR-G-1.1, 2014 [25]
	National regulations on nuclear safety, quality assurance and control of nuclear activities in Romania	Ensuring compliance with national requirements and increasing the level of control of the nuclear activities	- high implementation complexity and - need for periodic updating according to the evolution of international regula-tions	Nuclear activities and quality management in Romania	Normele CNCAN (România), 2025 [9]
Institutional Reports and Strategic Documents	Report on the activities of research, development and management in the nuclear field in Romania	Provides up-to-date information on strategic directions and national infrastructure in nuclear field	- predominantly institutional focus and - applicability limited to the national context	Research, development and management in the nuclear field in Romania	RATEN 2024 [26]
	Documents and reports on quality management, operation and Development strategy at the Cernavoda nuclear power plant	It provides applied information on implementation of quality and management requirements in the nuclear installations	- predominantly specific applicability organizational context of SNN	Operation of nuclear installations and quality management in Romania	Nuclearelectrica (SNN), 2022 [27]
	Documents and international security guidelines quality management and evaluation suppliers	It offers an international framework of Reference and good practices for the nuclear industry	- requires adaptation to regulations and conditions specific to each Countries or organizations	Safety Management, Assurance quality and supplier evaluation in the nuclear industry	International Atomic Energy Agency – IAEA, 2026 [28]
Reports and Studies Specialty	Usage analysis artificial intelligence to accelerate applications and Nuclear Processes	Highlights the potential of AI for process optimization and predictive analytics	- requires large volumes of data, and - validation of models in real conditions	AI applications and optimization processes in the nuclear industry	D. Brown, 2022 [29]
	Progress report and Global Nuclear Industry Trends	Provides an overview of the challenges and development directions of the industry nuclear	- predominantly macroeconomic and strategically, - with technical applicability Limited	Analysis of the nuclear industry and Strategic development dir ections	The World Nuclear Industry Status Report 2025 [30]
	Report on incidents and non-conformities associated with the supply of components for Nuclear Power Plants	Highlight the risks and Existing vulnerabilities in the nuclear supply chain	- predominantly based on the analysis of events and reported cases	Risk management and control suppliers in the nuclear industry	Ziedelis et al., 2012 [31]
	Strategic plan on the development and research in the field of	Highlight priorities research and emerging	- general strategic approach, - no details on	Research and development in the field nuclear	Aidala et al., 2023 [6]

	nuclear sciences	technologies in the nuclear field	Practical implementation		
Audits and Traditional inspections	Requirements for the implementation of insurance programmes quality and the performance of the Audit in nuclear installations	Standardised framework for quality control and conformity assessment	- complex processes and - high consumption of resources for implementation and monitoring	Quality assurance and plant audit nuclear	ASME – Quality Assurance Requirements for Nuclear Facility Applications, 2026 [1]
	Traditional methods of conformity assessment by audits, inspections and regular process checks and nuclear components	Standardised method recognised by the regulatory	- high time consumption and resources, - predominant character Reactive	Conformity assessment and control quality in the nuclear industry	IAEA, 2023 [3]
	Guide to quality assurance and control in Nuclear activities and installations	Provides recommendations for the implementation of control processes and verification of conformity	- predominantly traditional approach, - Reduced focus on modern digital technologies	Quality control and evaluation compliance in nuclear activities	Quality Assurance and Quality Control in Nuclear Facilities and Activities, 2020 [11]
	Rating systematic and extensive literature on methods and Criteria used in the selection of suppliers	Highlights the main approaches and criteria used in supplier selection and evaluation	- general approach, - no exclusive focus on the nuclear industry	Selection and evaluation of suppliers	Wetzstein et al., 2016 [12]
	Guide on the evaluation and qualification of commercial products used in nuclear safety systems	Improves control and traceability components used in nuclear applications	- requires additional verification and documentation proces ses	Evaluation of commercial products for use in industry nuclear power	DOE-HDBK – Commercial Grade Dedication Application Handbook, 2019 [10]
	Guide to the Procurement and Valuation of Industrial Products used in applications with nuclear power safety features	Supports the implementation of quality requirements and improvement supplier selection processes	- specific applicability to certain types of components, and Processes	Procurement and evaluation of plant products for nuclear	John et al., 2022 [32]
Non-destructive testing (NDT)	Comprehensive analysis of modern test methods and Non-destructive evaluation for advanced structures and components	Allows defect detection without damage components and increases the reliability of inspection processes	- requires specialized equipment and - qualified personnel for Interpretation of results	Inspection and evaluation of components used in industry nuclear power	Abdollahi-Mamoudan et al., 2025 [15]
	Using ML machine learning techniques in NDT applications for the analysis of complex ultrasonic signals	Improves defect detection and accuracy of interpretation of inspection data	- requires large volumes of data, and - validation of the models used	NDT and ultrasonic analysis in Industrial and Nuclear Applications	Krishnan et al., 2026 [22]
	Non-destructive inspection methods applied to components additively manufactured for use in nuclear installations	Enables component integrity assessment without damage to their structure	- the complexity of the evaluation of additively manufactured components, and - the need to validate methods	Additively Manufactured Components Inspection in Industry nuclear power	Lamberti et al., 2024 [33]
	Analysis of modern test methods and applications and non-destructive evaluation for structures and components Advanced	Highlight modern trends and apps emerging NDT technologies	- requires the integration of multiple methods and - specialized expertise for interpreting results	Assessment and monitoring of the integrity of structures and industrial components	Abdollahi-Mamoudan et al., 2025 [15]
	Analysis of monitoring and evaluation techniques cables used in nuclear power plants	Allows the identification of degradation and the prevention of defects in electrical systems	- Requires continuous monitoring and - Advanced data interpretation methods	Monitoring and evaluation of cables in nuclear power plants	Ghaforian et al., 2025 [34]

	Guide to quality assurance and control in nuclear activities and installations, including processes inspection and verification	Provides recommendations for the implementation of control processes and conformity assessm ent	- predominantly traditional approach and - limitations on the integration of modern technologies	Quality control and inspection in Nuclear activities	Quality Assurance and Quality Control in Nuclear Facilities and Activities, 2020 [11]
	Using Augmented Ultrasonic Data to Drive Models Machine Learning in NDT Applications	Improves the performance of ML models and increases the accuracy of defect detection	- requires augmented data validation and - Additional compu-tational resources	Ultrasonic analysis and machine learning applications in Non-destructive tes-ting	Virkkunen et al., 2021 [21]
	Technologies associated with ultrasound (UT) testing, radiography with X-rays, ground penetrating radar (GPR) and thermography, Integrated with advanced sensors and machine learning methods	Increasing the accuracy of defect detection and Automation of inspection processes	- requires advanced technical infrastructure and - ML model validation	Inspection and monitoring of structures and industrial and nuclear compon ents	Abdollahi-Mamoudan et al., 2025 [15]
Evaluation / Analysis risk-based	Commercial Component Valuation Method (COTS) used in electrical and instrumentation and control equipment (I&C) relevant to safety in nuclear installations	Enables controlled use of commercial components and improves the flexibility of procurement proces ses	- requires rigorous verification and validation processes for applications with safety features	Evaluation of COTS components for nuclear installa-tions	Arians et al., 2024 [35]
	Guide to the suitability assessment of commercial products used in nuclear power plant safety systems	Improves compliance control and reduces the risks associated with the use of commercial products	- requires additional verification processes, and - technical documen-tation	Evaluation of commercial products for safety systems nuclear power	IAEA – Suitability Evaluation of Commercial Grade Products for Use in Nuclear Power Plant Safety Systems, 2024 [2]
	Guide to Applying the Commercial Grade Dedication (CGD) Process in the evaluation of commercial components used in nuclear installations	Ensures traceability and verification compliance of components used in applications with Safety features	- complex evaluation processes and technical documen-tation	Evaluation and qualification of commercial components for Nuclear industry	DOE Handbook – Commercial Grade Dedication Application Handbook, 2019 [10]
	Quantifying uncertainties and risk-based decisions by integrating statistical descriptions of input parameters, and of defect distribution	Enables probabilistic integrity assessment structures and improved decision-making	- requires complex statistical models and - Large volumes of data	Structural integrity assessment and analysis risks in the nuclear industry	Chavoshi, 2021 [36]
Intelligence artificial intelligence (AI) and Machine Learning	AI and ML applications within the industrial ecosystem and Spanish Nuclear Research	Automation, high efficiency, analysis and the use of computer vision and Data-driven modeling	- Requires large volumes of data and - model validation processes	Inspections, risk assessment and image analysis	Ramos et al., 2024 [5]
	The use of artificial intelligence to manipulate and analysis of large volumes of data of different types and complexity	Enables rapid data processing and development of Advanced predictiv e models	- requires computational infrastructure and - validation of the generated results	Data analysis and optimization processes in the nuclear industry	D. Brown, 2022 [29]
	Using AI for model optimization, risk assessment in real-time,	Increasing predictive capability, and	- requires model validation, and - integration into	Risk assessment and process optimization in	Badawi, 2025 [37]

	accident prediction and fuel management nuclear	Improving decision-making	existing infrastructures	industry nuclear power	
	Use of digitization, high-performance computing technologies performance and advanced data processing methods in Nuclear applications	Increasing processing capacity and Improving complex analytics	- requires hardware and software infrastructure Advanced	Nuclear research and data analysis	Aidala et al., 2023 [6]
	Data-driven equipment health assessment frameworks and machine learning methods	Enables predictive monitoring and improving the assessment of the state of the systems, and structures	- requires large volumes of data, and - Validation of predictive models	Monitoring and evaluation of the condition of structures and systems in nuclear facilities	Sandhu et al., 2023 [38]
	Systematic synthesis of machine learning applications and deep learning for corrosion and crack detection in environments nuclear	Improves defect detection and allows the development of predictive analysis methods	- requires large data sets, and - validation of ML/DL models in real conditions	Corrosion and crack detection in nuclear installations	Allah et al., 2025 [39]
Management Knowledge & Regulation	Knowledge management analysis as a direction of Evolution of nuclear regulation and safety	Supports knowledge transfer and Improving decision-making	- requires the integration of organizational processes, and - continuous updating of information	Knowledge management and regulation in industry nuclear power	Beaupre, 2025 [13]
	Nuclear Supply Chain Management Document and the integration of organisational and Regulation	Supports the coordination of processes and improving information management, and suppliers	- Requires continuous updating of processes and - adapting to regulatory requirements	Supply chain management and regulation in Nuclear industry	Agenția Internațională pentru Energie Atomică – IAEA, 2026 [28]
Digital Twin	Real-time modeling and simulation of systems and industrial equipment	Continuous monitoring, predictive maintenance and optimizing system performance	- high complexity of implementation and - the need to integrate a large volume of data	Predictive maintenance and process optimization in Nuclear industry	Mondal et al., 2024 [14]
	Smart reliability methodologies for Engineering systems, based on advanced data analytics and predictive models	Improves performance monitoring and assessing the reliability of complex systems	- requires the integration of large volumes of data, and - Validation of predictive models	Monitoring and evaluation of the reliability of systems engineering and nuclear	Liu et al., 2025 [40]
	Data-driven frameworks for system health assessment structures through the use of predictive methods and smart technologies	Enables continuous monitoring and Improving the evaluation of systems performance	- requires large volumes of data, and - Validation of predictive models	Monitoring and evaluation of the condition of structures and systems in nuclear facilities	Sandhu et al., 2023 [38]
	The synergistic role of advanced production and twins Digital Transformation in the Transformation of the Nuclear Sector	Enables process optimization, real-time monitoring, and Improving predictive maintenance	- high complexity of implementation and integration of Data	Digital transformation and process optimization in Nuclear industry	Mondal et al., 2024 [14]
Blockchain	Ensuring traceability and security data in the nuclear supply chain	Transparency, traceability and fraud prevention	- Difficult integration and - low technology maturity in nuclear applications	Supply chain and traceability in the industry nuclear power	Ecemis, 2024 [16]
	The impact of blockchain technology on the sustainable management of supply chain	Improving traceability and security of information exchange	- requires digital infrastructure and -Process standardization	Supply Chain Management	Khadka, 2024 [17]
	Integrating AI and blockchain technologies	Automation and Processing	- High complexity of implementation and	Smart technologies and	Jani and Khan, 2026 [41]

	into industrial processes and intelligent production	Improvement and data security	integration Technological	industrial proces ses	
	Implications of counterfeit, fraudulent and suspects in the nuclear supply chain	It highlights the risks associated with security and traceability of nuclear components	- requires advanced verification and control mechanisms suppliers	Security of the nuclear supply chain	Hobbs et al., 2024 [4]
IIoT and Communica-tion	Real-time performance analysis of communication used in the Industrial Internet of Things (IIoT)	Continuous monitoring, data integration and Improving real-time communication	- security, interoperability and latency issues	Process monitoring and industrial contro l	Behnke and Austad, 2023 [19]
	Evaluation of industrial communication protocols for integration of monitoring equipment and software systems	Improves interoperability and exchange data between industrial systems	- cross-platform compatibility and integration issues different	Industrial monitoring and software system integration	Tapia et al., 2023 [20]
Research Directions and Innovation – Trends 2024-2026	Application of the Commercial Grade Dedication (CGD) process for the qualification of commercial components used in installations nuclear	Increasing traceability and reducing risks associated with commercial compo-nents	- complex evaluation processes and technical documen-tation	Evaluation and qualification of components for applications nuclear	DOE Handbook – Commercial Grade Dedication Application Handbook, 2019 [10]
	Procurement and valuation guide industrial products used in applications with Nuclear Safety	Improves quality control and supplier selection	- requires the implementation of rigorous verification processes	Procurement and evaluation of plant products nuclear	John et al., 2022 [32]
	Analysis of risks and events associated with the supply chain Supply of nuclear components	Highlight vulnerabilities and risks existing in the nuclear supply chain	- predominantly based on incident and event analysis reported	Risk management in the nuclear supply chain	Ziedelis et al., 2012 [31]
Sources of Documentati on Continue	International platforms and documents used for continuously updating the information and requirements in the Nuclear industry	Access to up-to-date information and best practices international	- the need for permanent verification and updating of the information	Documentation and monitoring of developments in the industry nuclear power	Agenția Internațională pentru Energie Atomică – IAEA, 2026 [28]
	Industry Trends & Evolution Report nuclear power globally	It provides an up-to-date picture of the challenges and development directions of the industry	- predominantly strategic and general approach	Monitoring industry developments and trends nuclear power	The World Nuclear Industry Status Report 2025 [30]

In contrast, modern technologies such as AI, *Digital Twin*, and IIoT support a proactive approach through continuous process monitoring and early detection of defects or non-conformities. As a result, they can improve the efficiency of control activities, reduce operational costs, and support better decision-making.

However, the analysis indicates that implementation of advanced technologies is constrained by several factors, including the complexity of integration into existing systems, the need for significant investment, and the absence of standardized application models in the nuclear industry. In addition, misalignment between regulatory requirements and the maturity of available technologies may hinder their wider adoption.

An important aspect highlighted is the need to integrate these methods into a unitary framework, which allows the correlation of information from different sources and the efficient use of data in supplier control processes. This aspect suggests that the development of integrated analysis and optimization models becomes an essential direction of research, having the potential to contribute to increasing the level of safety and improving the performance of quality assurance systems.

These limitations highlight the need to develop integrated approaches, based on the use of advanced methods of analysis and modelling, which allow the correlation of information, the, reducing redundancies and improving the performance of supplier evaluation and monitoring processes.

The analysis of the sources presented in Fig. Table 2.1 highlights the fact that recent research in the field of quality assurance in the nuclear industry is mainly oriented towards the integration of modern technologies into supplier control processes. The analyzed studies emphasize the importance of using artificial intelligence, technologies *Digital Twin*, *blockchain* and IIoT to increase the level of automation, improve traceability and develop predictive methods of analysis and quality control.

Based on these aspects, it becomes appropriate to develop integrated and interdisciplinary approaches, capable of combining traditional quality assurance methods with modern analysis and modeling technologies. These research directions can contribute to optimizing supplier assessment and monitoring processes, reducing the risks associated with supply chains and improving the performance of quality assurance systems in the nuclear industry.

6. LIMITATIONS AND GAPS IDENTIFIED IN THE LITERATURE

From the analysis of the weightings of the limitations resulting from the bibliographic sources analyzed, they can be derived certain research directions that can be addressed even within preliminary objectives (Fig. 2). Gap classes were ranked according to frequency of occurrence in sources (number of sources). The hierarchy shows that there are some limitations that occur with reduced frequency (1−3) and others with frequencies of 4−10. A high frequency does not necessarily mean a direction to follow, but it certainly points to a quasi-general problem of great importance. Of course, the choice was also based on the possibilities regarding resources and cooperation with researchers in the field in the framework of doctoral research, as well as accessibility to components and manufacturers in the nuclear industry.

Thus, the following research directions emerged:

- Application of digital technologies in quality and audit models;
- Integration of modern methods and technologies;
- Solving compatibility and integration issues;
- Solutions allowing a continuous adaptation of methods or models;
- Realization of validation of methods/models in real conditions.

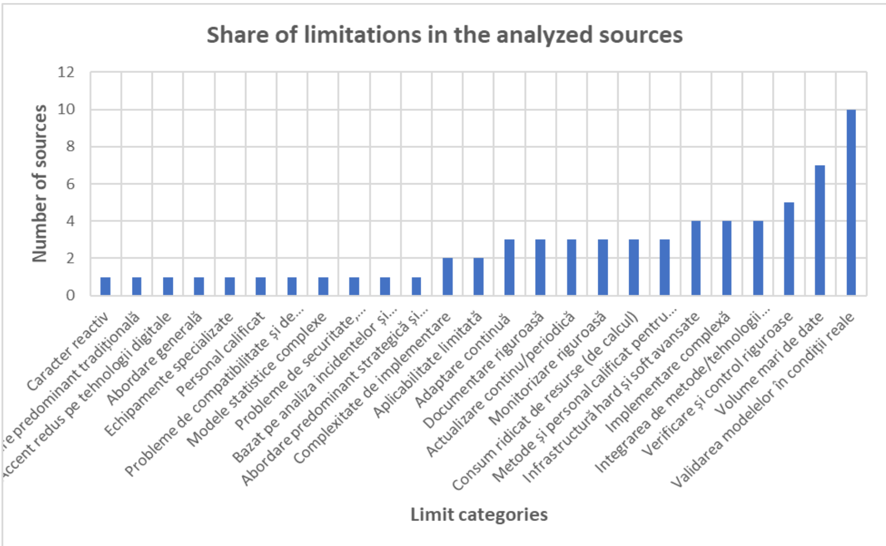

Fig. 2. Weight of limitations in the sources analysed.

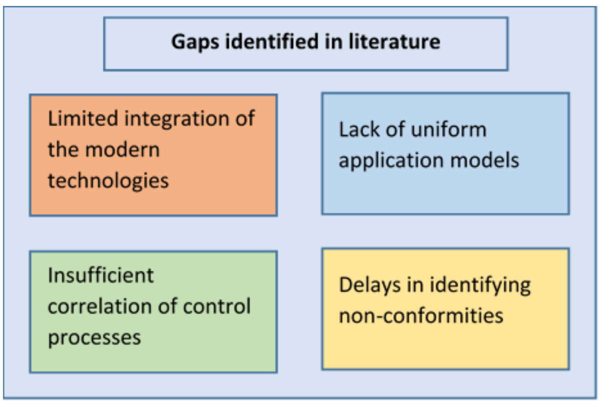

Fig. 3. Gaps identified in nuclear industry supplier evaluation and monitoring processes.

The literature review on quality assurance and supplier evaluation in the nuclear industry identifies significant gaps despite the rapid development of modern methods and technologies.

Although numerous studies examine advanced technologies such as AI, *Digital Twin*, *blockchain*, and IIoT, they generally address these tools in isolation rather than within an integrated framework for analysis and optimization [5, 14].

The main gaps identified in the literature on evaluation processes and vendor monitoring can be synthesized conceptually, as illustrated in Fig. 3.

A first major gap is the absence of integrated models that connect supplier audit, evaluation, and monitoring processes with the use of modern technologies. Most studies focus either on traditional methods or on digital technologies, without showing how these approaches can be combined coherently in practice.

The literature also shows limited attention to optimizing quality assurance processes in complex supply chains. Supplier evaluation is often conducted through standardized methods that do not adequately reflect specific risks or interdependencies across the supply chain.

Another underdeveloped area is the integration of modern technologies into existing systems under the nuclear industry's strict regulatory constraints. The absence of clear methodological frameworks limits practical implementation and reduces the potential to improve quality assurance processes.

Together, these gaps indicate the need for advanced analysis and optimization models that integrate modern technologies into supplier evaluation processes in order to improve efficiency, reduce risk, and strengthen quality assurance performance.

7. PROPOSED FUTURE RESEARCH

On the basis of limitations and gaps resulted from the anlisys of the studied bibliographic sources, a set of possible future research subjects were outlined and grouped on categories:

A. Risk management in the assessment and monitoring processes of suppliers in the nuclear industry:

- establishing the methodological framework for the management of risk associated with suppliers;
- defining risk factors and evaluation criteria;
- correlation of risk level with nuclear safety and quality assurance requirements.

B. Development of a risk-based vendor assessment and classification methodology:

- developing evaluation criteria and indicators;
- developing a model for classifying and ranking suppliers according to the level of risk;
- integrating evaluation results into the decision-making process.

C. Development of a system for prioritizing audit, inspection, supervision and monitoring activities:

- devising a method for planning control activities according to the level of risk;
- developing mechanisms for continuous monitoring of supplier performance;
- integrating the results of audits, inspections and monitoring into the decision-making process.

D. Integration of traceability and compliance control requirements into the developed methodology:

- integrating traceability requirements into the assessment and monitoring process;
- developing compliance control mechanisms;
- integration of measures to prevent the introduction of non-compliant or counterfeit products (CFSIGNS.

E. Validation of the methodology developed under conditions specific to the nuclear industry:

- validation of the methodology by applying it to representative case studies;
- evaluating the performance of the methodology in relation to existing practices;
- formulation of recommendations for the implementation of the methodology in evaluation processes and vendor monitoring.

8. CONCLUSIONS

The literature shows that quality assurance systems in the nuclear industry have evolved from audit- and inspection-based approaches toward more digital, automated, and predictive models.

Technologies such as artificial intelligence, Digital Twin, blockchain, and IIoT create opportunities to improve supplier evaluation and monitoring by enabling more proactive, data-driven identification of non-conformities and risks.

However, their adoption remains limited by integration complexity, regulatory constraints, and the absence of unified application models tailored to the nuclear industry. Existing approaches also remain fragmented, particularly in how they connect supplier audit, evaluation, and monitoring activities.

The analysis therefore points to a broader need for integrated methodological frameworks that combine multiple information sources, support proactive risk identification, and align technological innovation with regulatory requirements. This need provides the basis for the objectives and preliminary directions of the doctoral research presented in the next chapter.

Classical methods, while remaining essential for ensuring compliance and complying with regulatory requirements, are characterized by a predominantly reactive character and high resource consumption.

In contrast, modern technologies, such as AI, *Digital Twin* or IIoT, allow a proactive approach, based on continuous monitoring of processes and anticipation of the occurrence of defects or non-conformities. These methods lead to increased efficiency of control activities, reduced operational costs and improved decisions.

However, the analysis highlights that the implementation of advanced technologies is limited by a number of factors, such as the complexity of their integration into existing systems, the, the need for significant investment and the lack of standardized application models in the nuclear industry. In addition, differences between regulatory requirements and the level of maturity of technologies can be obstacles to the widespread adoption of these solutions.

An important aspect highlighted is the need to integrate these methods into a unitary framework, which allows the correlation of information from different sources and the efficient use of data in supplier control processes. This aspect suggests that the development of integrated analysis and optimization models becomes an essential direction of research, having the potential to contribute to increasing the level of safety and improving the performance of quality assurance systems.

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Based on these aspects, it becomes appropriate to develop integrated and interdisciplinary approaches, capable of combining traditional quality assurance methods with modern analysis and modeling technologies. These research directions can contribute to optimizing supplier assessment and monitoring processes, reducing the risks associated with supply chains and improving the performance of quality assurance systems in the nuclear industry.

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