

Digital Transformation of the Nuclear Industry: Leveraging Robotics, AI, and Digital Twins for Standardised, Safe, and Efficient Operations

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Abstract: The nuclear back-end is experiencing a pivotal digital transformation driven by the integration of robotics, artificial intelligence (AI), and digital twin (DT) technologies. These innovations hold strategic potential to enhance safety, efficiency, and standardisation across decommissioning, waste management, and site remediation. Using the Technical, Economic, Commercial, Organisational, and Political framework (TECOP) and Five Case Models, this paper critically assesses the value, deployment readiness, and integration barriers of these digital tools across technical, organisational, and regulatory domains. Emphasis is placed on robotics in 5D contexts, the nuclearization challenge, and the role of DT and Building Information Modelling (BIM) in scenario planning and compliance. Persistent obstacles, including fragmented certification, cybersecurity vulnerabilities, limited interoperability, and resistance to change, are analysed using data from expert surveys and project experience. Targeted strategies are proposed to address these issues and accelerate technology readiness and regulatory harmonisation. The contributions of EU-funded initiatives such as HARPERS, DORADO, and XS-Ability are highlighted as catalysts for safe and scalable digital innovation. By providing actionable recommendations, this paper supports policymakers, industry leaders, and technology developers in advancing the digital evolution of the nuclear back-end.

1 INTRODUCTION

The nuclear back-end encompassing decommissioning, radioactive waste management, and site remediation represents some of the most technically demanding, hazardous, and stringently regulated domains within the energy sector (IAEA, 1992). Traditional operational approaches frequently fall short in delivering the scalability, efficiency, and transparency required to address contemporary safety and sustainability objectives, particularly in the context of aging infrastructure and increasing regulatory oversight (Bogue, 2011). In response, industry stakeholders are progressively embracing digital transformation strategies, including the

deployment of robotics, artificial intelligence (AI), and digital twin (DT) technologies (Smith et al., 2020; Benkrid et al., 2025).

These advanced tools are reshaping the landscape of monitoring, maintenance, and dismantling activities in nuclear facilities. Robotic systems facilitate remote interventions in high-radiation or structurally compromised environments (Michel et al., 2025), AI-driven analytics support predictive maintenance and complex decision-making (Arhouni et al., 2025; Selvam et al., 2025), while DT and Building Information Modelling (BIM) enable advanced scenario simulation, regulatory compliance, and enhanced stakeholder engagement (Virando et al., 2024; Oti et al., 2022). Despite their potential, the integration of these technologies

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remains hampered by persistent technical, organisational, and regulatory challenges, including the “nuclearization” of commercial solutions, cybersecurity vulnerabilities, interoperability limitations, and fragmented certification pathways (Skilton et al., 2023; Wong et al., 2024).

This paper critically examines the implementation and integration of robotics, AI, and digital solutions in the nuclear back-end. Leveraging the TECOP and Five Case Models, it analyses their strategic value, maturity levels, and principal barriers to adoption. Drawing on insights from recent EU-funded initiatives, such as HARPERS, DORADO, and XS-Ability, the study offers evidence-based recommendations to support policymakers and industry stakeholders in advancing safe, standardized, and future-proof digital innovation.

2 ROBOTIC TECHNOLOGIES IN THE NUCLEAR BACK-END

This section examines the role of robotics in the nuclear back-end, focusing on their operational value in hazardous and restricted-access environments. Applying the TECOP framework, it analyses both the strategic benefits and the persistent integration challenges facing robotic technologies in decommissioning and waste management.

Key barriers include the absence of harmonised certification schemes, insufficient testing infrastructure, and uncertainty surrounding first-of-a-kind (FOAK) systems. Robotics are particularly relevant for “5D” tasks Dirty, Dangerous, Difficult, Dull, and Dear, where they enhance safety and efficiency. However, broader deployment is constrained by infrastructural gaps, organisational risk aversion, fragmented knowledge sharing, and complex regulatory pathways. These factors continue to shape the pace and scale of robotics adoption across the sector.

2.1 Strategic Importance and Advancing Robotic Capabilities

Over recent decades, robotic systems have progressed from basic manipulators to advanced robotic systems have evolved from basic manipulators to advanced platforms capable of executing complex tasks in hazardous nuclear back-end environments (Bogue, 2011; Szőke et al., 2023). In decommissioning scenarios marked by intense radiation and limited access, robotics improve safety by reducing worker

exposure (IAEA, 1992) and enhance operational efficiency through remote inspection, sampling, and dismantling (Kazemi et al., 2025; Shin et al., 2018).

Recent advances in AI, computer vision, and sensor technologies enable semi-autonomous navigation and perception. Mobile robots can now map radiation zones and adapt in real time, minimising human intervention and operational delays (Benkrid et al., 2025; Fauquet-Alekhine & Bleuze., 2023).

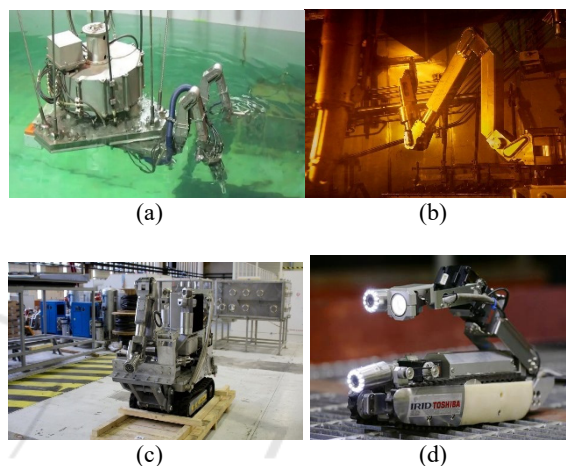


Figure 1: Representative Mobile Rovers and Manipulator Arms Demonstrating Remote Robotic Operations in Nuclear Decommissioning; Manipulator arms (a, b) and mobile rovers (c, d) developed by Toshiba (a, d) and CEA France (b, c) for nuclear remote operations.

2.2 Applications in 5D Environments

The adoption of robotic systems in nuclear operations is fundamentally motivated by the so-called “5D” criteria: Dirty, Dangerous, Difficult, Dull, and Dear. These categories correspond to conditions where direct human intervention is impractical, unsafe, or economically prohibitive (IAEA, 1992). In the nuclear back-end, such as decommissioning, waste management, and contaminated facility inspection, robotics have become indispensable. Routine applications now include inspection, environmental sampling, precision cutting, decontamination, and waste segregation (Bogue, 2011).

These demands have led to diverse robotic solutions, from standard ROVs for underwater inspections to custom manipulators for hazardous hot cells, such as those developed for Fukushima or by CEA France (see Figure 1). Deploying such systems requires multidisciplinary expertise and strict adherence to nuclear qualification standards.

Nevertheless, major technical and regulatory hurdles remain, particularly around radiation tolerance, remote operability, and system reliability in complex nuclear environments.

2.3 Deployment Gaps and Nuclearisation Challenges

While robotics are mature in aerospace and manufacturing (Szöke et al., 2023; Smith et al., 2023), their deployment in nuclear contexts is hindered by the need for radiation-hardening and compliance with strict safety standards (Bogue, 2011; IAEA, 1992). Many components degrade under radiation and require redesign, lowering their Technology Readiness Level (TRL) when adapted for nuclear use (Tugal et al., 2023; Swaminathan et al., 2025).

Additionally, nuclear sites pose complex communication and control challenges (Fauquet-Alekhine & Bleuze, 2023). The absence of standardised procedures and diverse site conditions further limit technology transfer and industrial uptake (Benkrid et al., 2025; Michel & Amoyal, 2025).

2.4 Infrastructure for TRL Advancement

Advancing robotic technologies from early concept to operational deployment in the nuclear sector requires dedicated infrastructures and systematic evaluation frameworks (Michel & Amoyal, 2025). The NASA Technology Readiness Level (TRL) scale (Swaminathan et al., 2025) is commonly used to assess maturity:

- **TRLs 1–3:** early research and proof of concept,
- **TRLs 4–6:** validation in lab or relevant environments,
- **TRLs 7–8:** prototype demonstration and integration,
- **TRL 9:** proven systems in operational conditions.

Notably, even mature technologies (TRL 8–9) from other fields often require requalification and are assigned lower TRLs for nuclear applications due to strict safety and radiation requirements, a process called “nuclearization” (Tugal et al., 2023).

Facilities like the UK National Nuclear User Facility for Hot Robotics (NNUF-HR) enable realistic testing, validation, and demonstration of systems, facilitating technology advancement and lowering barriers for SMEs (Bogue, 2011).

Surveys by groups such as the Expert Group on Robotics in the Nuclear Back-end (EGRRS) (NEA-

EGRRS) indicate that challenges persist across design, development, and integration phases, particularly adapting to legacy infrastructure and meeting certification standards.

Expanding dedicated testing infrastructures across Europe is vital to accelerate technology maturation and support widespread deployment (Szöke et al., 2023).

2.5 Barriers Identified by Expert Surveys

Recent expert surveys (Benkrid et al. 2025; Michel & Amoyal, 2025; Szöke et al., 2023) have highlighted that, despite improvements in technical infrastructures and validation frameworks, organizational and regulatory barriers persistently impede the uptake of robotics in the nuclear sector.

The main challenges identified include:

- **Risk aversion and reluctance to adopt first-of-a-kind systems**, often due to the sector’s strong safety culture and strict regulatory scrutiny.
- **Limited cross-sector communication and knowledge sharing**, which restricts awareness of available solutions and best practices.
- **Unclear or fragmented regulatory requirements**, making it difficult for developers to navigate certification and approval processes.
- **Lack of sustained funding and institutional support**, especially for low- and mid-TRL systems that require additional demonstrations before deployment.
- **Insufficient training and expertise** bridging robotics and nuclear safety domains.

These non-technical barriers result in prolonged pilot phases, slow market entry for emerging solutions, and underutilization of available robotic technologies.

Addressing these issues will require harmonized regulatory approaches, dedicated funding and demonstration programs, and stronger collaboration between operators, industry, regulators, and research organizations.

2.6 Regulatory and Organisational Bottlenecks

Despite advances in robotics for the nuclear sector, adoption remains limited by regulatory and

organisational challenges (Michel & Amoyal, 2025; Swaminathan et al., 2025). Complex and fragmented certification processes, coupled with inconsistent regulatory frameworks, create significant hurdles for developers, especially those new to nuclear requirements (IAEA, 1992; Szőke et al., 2023).

Institutional risk aversion, rooted in the sector's strong safety culture, often leads to reluctance in deploying novel or highly autonomous systems without extensive validation, resulting in prolonged pilot phases and slow operational uptake.

The integration of AI further complicates certification due to issues around explainability, fail-safes, and cybersecurity, which are not yet fully addressed by existing regulations (Tugal et al., 2023). Harmonisation of standards and regulatory processes across Europe remains limited, increasing development costs and barriers for SMEs.

Overcoming these bottlenecks requires regulatory innovation, greater cross-sector collaboration, and cultural shifts within organisations to embrace digital and autonomous technologies. Initiatives such as the European Expert Group on Robotics and projects like CLEANDEM (Michel, M., et al. 2023) highlight the need for coordinated efforts to facilitate robotics deployment in the nuclear industry.

3 DIGITAL TECHNOLOGIES IN NUCLEAR BACK END

Digital technologies such as Digital Twins (DT) and Building Information Modelling (BIM) are increasingly seen as strategic enablers for nuclear back-end operations, particularly in decommissioning and waste management (Szőke et al., 2023). These tools support improved planning, safety, and regulatory compliance through advanced virtualisation and real-time data integration (Amin et al., 2021).

This section applies the TECOP framework to evaluate the deployment status of DT and BIM across technical, economic, commercial, organisational, and political dimensions. It outlines their core benefits, identifies key barriers to adoption, presents stakeholder insights, and concludes with targeted recommendations to accelerate implementation and digital innovation across the sector.

3.1 Strategic and Operational Benefits

DT and BIM technologies offer key advantages for nuclear decommissioning and waste management. By

simulating dismantling scenarios, they enable advanced planning, workflow optimisation, and early anomaly detection, reducing safety risks and enhancing decision-making. These tools also support accurate waste estimation, material tracking, and resource allocation throughout the decommissioning lifecycle.

DT and BIM further improve remote and robotic operations to limit human exposure in hazardous zones (Szőke et al., 2023). Real-time data integration enables condition monitoring and predictive safety management, while simulations enhance emergency preparedness (Amin et al., 2021).

From a regulatory standpoint, they streamline compliance by facilitating data reporting and supporting phased technology integration. DT/BIM platforms also strengthen knowledge management, training, and external communication by visualising complex operations.

3.2 Barriers to Adoption and Emerging Risks

Despite their advantages, DT and BIM face cybersecurity vulnerabilities, sensor and data limitations, and integration difficulties with legacy systems. Many organisations lack adequate infrastructure for secure data handling, and legacy records remain largely non-digitised.

Financial uncertainty and organisational resistance also constrain adoption, driven in part by rapid technological change and insufficient regulatory alignment. Without clear ROI and consistent certification, decision-makers remain hesitant to invest.

3.3 Stakeholder Insights and Priorities

According to the survey conducted in the context of this analysis, stakeholders identified dismantling scenario simulation as the highest-priority application of DT and BIM. This was followed by their use in regulatory review, project scheduling, site monitoring, and strategy development. There was also strong consensus around the usefulness of DT/BIM for environmental risk modelling and waste minimisation (Szőke et al., 2023).

However, these priorities are tempered by persistent concerns around cybersecurity, lack of interoperability, limited availability of commercial off-the-shelf solutions, and insufficient regulatory clarity (Szőke et al., 2023). These challenges were echoed across responses from both internal and external stakeholders.

Table 1: Mapping of identified enablers and blockers for DT/BIM implementation across TECOP dimensions.

TECOP Dimension	Enablers / Opportunities	Blockers / Challenges
Technical	Scenario simulation, safety monitoring, real-time data integration, robotics support	Sensor limitations, Legacy data, Low interoperability, Cybersecurity vulnerabilities
Economical	Lifecycle cost reduction	High initial investment, Lack of ROI evidence
Commercial	Technology-provider collaboration	Limited COTS solutions, Unclear business models
Organisational	Training and knowledge management, Change leadership	Skills gaps, Organisational resistance
Socio-Political	Improved transparency, public engagement, Modern image for young professionals	Public trust deficit, Regulatory misalignment, Lack of global standards

Table 1 summarises the key enablers and barriers to DT and BIM adoption in nuclear decommissioning using the TECOP framework. It highlights the most frequently cited opportunities, such as scenario simulation, enhanced safety monitoring, and improved public engagement, as well as major challenges including cybersecurity risks, high initial costs, limited interoperability, and regulatory misalignment. This structured overview supports the targeted recommendations provided in the following section by clarifying the interplay between technological promise and real-world constraints.

3.4 Recommendations for Effective Implementation

To unlock the full potential of DT and BIM technologies in nuclear decommissioning, several measures are recommended: (i) **Invest in enabling infrastructure**: Develop site-specific sensor systems and secure data platforms tailored to the nuclear context. (ii) **Launch targeted pilot projects**: Focus on use cases with high strategic relevance, such as dismantling scenario analysis and operator training to generate early value and build internal support.

(iii) **Develop integration standards**: Promote interoperability through shared data formats, cybersecurity protocols, and implementation frameworks. (iv) **Promote cross-sector collaboration**: Strengthen ties between nuclear stakeholders, technology providers, and regulatory agencies to accelerate knowledge exchange and regulatory harmonisation. (v) **Build workforce capacity**: Offer continuous training and establish change management strategies to reduce resistance and foster digital culture.

4 REGULATORY CHALLENGES AND STRATEGIES FOR ENABLING INNOVATION

The integration of advanced technologies such as autonomous robotics and artificial intelligence (AI) into nuclear decommissioning and waste management introduces not only technical but also profound regulatory challenges. Unlike incremental innovations, these emerging technologies often do not align with existing regulatory assumptions or categories (Szöke et al., 2023; Skilton et al., 2023). Their disruptive nature, combined with the high-risk profile of nuclear operations, demands regulatory frameworks that are adaptable, harmonized, and forward-looking.

4.1 Disruption of Established Regulatory Paradigms

The nuclear sector is governed by conservative regulatory regimes prioritising deterministic models and validated practices (Szöke et al., 2023). Emerging technologies especially AI and autonomous robotics, often fall outside existing validation frameworks, leading to uncertainty and delayed deployment.

Projects like SHARE and HARPERS call for adaptive, risk-informed regulations to match the pace of innovation while maintaining public trust (Michel et al., 2023).

4.2 Fragmentation and Lack of Harmonized Standards

One of the most significant barriers to adoption lies in the absence of internationally harmonized standards for the certification and deployment of robotics and AI technologies in sensitive sectors (Benkrid et al., 2025; Szöke et al., 2023). Regulatory requirements vary considerably across jurisdictions,

leading to fragmented certification pathways and increased complexity for multinational projects (Michel & Amoyal, 2025; Tugal et al., 2023). Technologies may require redundant testing and approval in each country, resulting in higher costs, procedural delays, and ultimately deterring investment and cross-border collaboration.

Moreover, this regulatory fragmentation hinders interoperability and slows down the development of common safety protocols. For developers and operators, navigating this patchwork of national requirements imposes a substantial administrative and financial burden that inhibits innovation.

4.3 Knowledge Gaps and Regulatory Grey Zones

Many tech developers lack familiarity with nuclear regulatory frameworks, leading to under- or over-designed solutions and unpredictable review processes (Smith et al., 2020; Szőke et al., 2023). FOAK systems face long approval timelines due to the absence of established categories and evaluation criteria (Michel & Amoyal, 2025).

Clarifying certification requirements and building cross-sector expertise are essential to de-risk innovation and reduce development costs.

4.4 Validation and Emerging Solutions

Validation of robotics and AI systems intended for hazardous environments is a complex, yet essential, step toward acceptance (Smith et al., 2020). Unlike conventional industrial tools, these systems must demonstrate robustness, reliability, and safety across a wide range of operational scenarios, including exposure to high radiation, limited accessibility, or degraded sensing environments. Current validation protocols, however, often fall short of addressing these extreme-use conditions (IAEA, 1992).

In response, innovative regulatory tools such as **regulatory sandboxes** are gaining attention (Michel & Amoyal, 2025). These controlled environments allow early collaboration between technology developers and regulators, enabling real-world testing of novel systems under limited scope and risk. By facilitating iterative feedback, sandboxes help refine both technology design and regulatory expectations (Smith et al., 2020). They offer a pragmatic path toward the development of realistic, risk-informed standards that can accelerate the safe deployment of advanced technologies.

4.5 Continuous Validation, Post-Market Surveillance, and Trust Building

Beyond initial certification, the long-term safety and reliability of deployed robotic and AI systems must be ensured through continuous validation and **post-market surveillance mechanisms** (Szőke et al., 2023). These mechanisms are critical in a high-risk sector such as nuclear decommissioning, where even minor system failures can have severe consequences. Real-time performance monitoring, incident reporting, and software updates must be integrated into regulatory expectations, allowing technologies to evolve while remaining within a validated operational envelope (IAEA, 1992).

These feedback loops not only enhance safety but also contribute to building **regulatory trust**. When regulators, operators, and technology providers share data and lessons learned from real-world use, future assessments become faster and more robust. Importantly, such processes help address the limitations of initial FOAK (first-of-a-kind) validations, enabling dynamic improvement of both technologies and regulatory practices over time.

4.6 Capacity Building and Collaborative Governance

The complexity and novelty of digital and autonomous technologies require **regulatory bodies themselves to evolve** (IAEA, 1992). Traditional expertise may no longer suffice to assess the nuanced behaviour of AI systems, the cybersecurity vulnerabilities of connected platforms, or the functional resilience of autonomous robots in radioactive environments. As such, **capacity building within regulatory authorities** is essential.

Dedicated training programmes, collaborative working groups, and participation in international standardisation efforts are all necessary to enhance regulators' ability to keep pace with innovation. Initiatives such as the OECD Working Group on new technologies demonstrate the value of cross-border dialogue and harmonised policy development.

Collaboration across sectors between nuclear operators, research institutions, digital technology providers, and regulators is another key enabler. Shared pilot projects, co-developed testing protocols, and transparent communication channels support mutual understanding and accelerate the co-creation of practical, innovation-friendly regulatory frameworks.

4.7 Clarifying Regulatory Requirements vs. Misinterpretations

In many cases, the perceived rigidity of regulatory frameworks stems not from actual legal constraints, but from **misinterpretation of requirements** (Smith et al., 2020). Differentiating clearly between what is truly mandated by regulation, what is a technical necessity, and what is an organisational habit is critical. This clarity can prevent overengineering, reduce unnecessary costs, and avoid project delays caused by conservative overcompliance.

Efforts should therefore include guidance documents, case studies, and knowledge exchange platforms to clarify **how existing regulations apply** to new technologies (2021 Szöke et al., 2023). These tools will help both developers and operators focus their efforts on genuine compliance priorities and avoid wasting resources on irrelevant or misunderstood constraints.

5 VALUE PROPOSITION OF ADVANCED TECHNOLOGIES

The integration of advanced technologies AI, robotics, and digitalisation is increasingly shaping nuclear back-end activities such as decommissioning, waste management, and site remediation (IAEA, 1992). These tools offer the potential to enhance safety, improve efficiency, and reduce long-term costs (Wong et al., 2024). Digital twins, autonomous systems, and analytics support smarter decision-making and risk mitigation.

However, adoption requires more than a cost-saving argument. A robust business case must address strategic alignment, operational feasibility, and long-term sustainability (Swaminathan et al., 2025). The Five Case Model provides a structured framework across five dimensions:

- **Strategic alignment**, particularly with goals such as enhanced safety and modernization.
- **Economic value**, emphasizing public benefits and cost-effectiveness.
- **Commercial viability**, ensuring market readiness and industrial uptake.
- **Financial assessment**, balancing initial investment against expected returns.
- **Managerial readiness**, focusing on regulatory compliance, project governance, and workforce capacity.

Despite growing interest, deployment remains constrained by fragmented regulation, limited standardisation, and integration gaps (Wong et al., 2024). The HARPERS project proposes a structured methodology combining the Five Case Model with the TECOP framework to assess not only financial outcomes but also technical feasibility, regulatory alignment, and socio-political impact.

5.1 The Need for Change

Current decommissioning and waste handling practices rely heavily on outdated, manual methods that are not only cost-intensive but also pose health and environmental risks. Inconsistent technology qualification processes, especially across jurisdictions, result in delayed innovation uptake and inefficiencies in waste processing. Robotics and automation remain underutilized, with challenges in reliability, cost justification, and regulatory acceptance hindering wider deployment (Michel & Amoyal, 2025).

Similarly, digital twin and BIM technologies, despite their planning and simulation benefits-face barriers such as poor interoperability, cybersecurity concerns, and lack of certification standards.

These systemic limitations underscore the urgent need for harmonization and international cooperation to standardize practices, accelerate innovation adoption, and improve operational outcomes.

5.2 Building the Economic Case

The HARPERS framework guides the development of a robust economic case through four key steps: identifying evaluation criteria (TECOP attributes), analysing impacts and risks, comparing change scenarios, and making informed go/no-go decisions (Szöke et al., 2023). The evaluation spans safety improvements, cost reductions, time efficiencies, and sustainability considerations.

Each technological area, waste management, robotics, and digital twins, has been assessed via high-level TECOP analyses. These reveal that:

- **Technical:** Standardization enhances reliability and scalability but requires robust integration with legacy systems and advanced safety features (IAEA, 1992).
- **Economic:** While upfront costs can be high, lifecycle savings from improved efficiency and reduced waste volumes justify investment (Michel & Amoyal, 2025).
- **Commercial:** Unified standards can stimulate market growth and reduce

investment risks through predictable qualification pathways (Wong et al., 2024).

- **Organizational:** Success depends on workforce training, internal acceptance, and change management strategies (Oti et al., 2022).
- **Socio-Political:** Public trust and regulatory alignment are critical; these can be improved through stakeholder engagement and transparency (Kolditz et al., 2023).

5.3 Insights from Practical Applications

The framework was applied to real-world use cases (e.g., Centraco Melting Unit, Studsvik inDRUM, NNL’s EASD, Magnox DT, and Fukushima robotics). Across all, benefits such as enhanced worker safety, cost savings, and improved timelines were observed (Michel & Amoyal, 2025). However, challenges persist around capital costs, workforce resistance, and regulatory complexity.

Interactive discussions at DigiDECOM 2024 further highlighted the need to adopt a broader view of return on investment (ROI), considering not only direct cost savings but also long-term strategic gains such as risk reduction, regulatory resilience, and skill development (Szóke et al., 2023).

Table 2: Summary of key challenges and levers identified in the HARPERS project for successful adoption of robotics, digital tools, and advanced decontamination technologies in the nuclear back-end.

Dimensions	Barriers	Enablers
Technical	Fragmented qualification protocols, interoperability gaps	Standardized frameworks, digital integration
Economic	High upfront costs, uncertain ROI	Lifecycle savings, pooled R&D funding
Commercial	Market hesitation, lack of certified products	Cross-sector partnerships, shared procurement mechanisms
Organizational	Workforce resistance, limited skills	Training programs, leadership engagement
Socio-Political	Regulatory fragmentation, public scepticism	International harmonization, early stakeholder involvement

5.4 Recommendation for Policy Markers

The findings present a compelling case for policy-led harmonization in three critical domains:

- Waste treatment and decontamination technologies
- Robotics and automation in dismantling and waste operations
- Digital twin and advanced BIM integration

Policymakers are urged to lead the establishment of international standards, develop collaborative regulatory testing environments, and promote data interoperability (IAEA, 1992). Addressing societal concerns, such as job displacement or data privacy requires transparency, community engagement, and inclusive governance mechanisms.

By adopting a standardized and collaborative approach, the nuclear sector can overcome systemic barriers and unlock the full value of advanced technologies, ensuring a safer, more efficient, and sustainable future for nuclear back-end operations.

6 SAFETY AND SECURITY IN DIGITAL NUCLEAR OPERATIONS

Digital transformation, driven by the integration of robotics, artificial intelligence (AI), and digital twins (DT), presents major opportunities to strengthen safety and security in the nuclear operation while enhancing operational efficiency (Smith et al., 2020; Virando et al., 2024). Safety requirements in this domain are exceptionally stringent, not only due to radiological hazards but also the persistent threats of malicious attacks and cyber intrusions.

Robotics significantly reduces operator exposure by performing hazardous tasks such as inspection, maintenance, and decontamination, thereby contributing substantially to on-site physical safety (Smith et al., 2020; Wong et al., 2024). Autonomous robots further bolster physical protection through surveillance and intrusion detection.

AI plays a critical role in nuclear back-end safety, enabling predictive maintenance by identifying failures early through sensor data analysis, and enhancing cybersecurity via anomaly detection and the protection of information networks (IAEA, 1992).

Digital twins are essential for real-time monitoring and risk assessment. They facilitate the simulation of incidents, cyber-physical attacks, and

technical failures, supporting the continual testing and refinement of safety and security protocols (Virando et al., 2024; Eckhart & Ekelhart, 2019).

However, the adoption of these technologies also introduces new risks, such as cybersecurity vulnerabilities, software/ hardware failures, and human-machine interface challenges. Robotic systems must therefore be designed with redundancy, fail-safe mechanisms, and subjected to rigorous validation protocols (Smith et al., 2020; Wong et al., 2024). Robust cybersecurity measures are vital for both AI and networked robotics, including encryption, access controls, behavioral monitoring, and compliance with relevant standards (Wen et al., 2025).

For digital twins, the reliability and accuracy of models and data are critical; any compromise may result in improper responses to incidents. Consequently, these systems require continuous updates, real-world validation, and architectures that are resilient to intrusions (Holmes et al., 2021).

Ultimately, the success of this transformation also depends on human expertise, continuous operator training, compliance with regulatory frameworks (such as ISO 27001, ISO 42001, GDPR, and the EU AI Act), and a proactive approach to emerging safety and cybersecurity challenges throughout the lifecycle of digital solutions (Wen et al., 2025; Holmes et al., 2021).

7 EU-FUNDED SOLUTIONS: DORADO AND XS-ABILITY

Two EU-funded projects, XS-Ability and DORADO, are addressing major technical and organisational barriers that hinder the deployment of robotics and digital solutions in nuclear decommissioning.

The **XS-Ability** project (Michel & Amoyal, 2025), funded by EURATOM, focuses on the development of modular, autonomous robotic systems for in-situ characterisation in hard-to-access, highly radioactive nuclear environments. XS-Ability platforms are designed to operate with minimal human intervention in environments that present radiological, spatial, and logistical constraints. The robotic systems incorporate radiation-tolerant sensors (e.g., gamma spectrometers, LiDAR, structured light scanners), onboard AI for data fusion and autonomous decision-making, and wireless communication for remote supervision. The project also emphasises modular payload architecture to allow rapid adaptation to mission-specific needs.

Technical validation is carried out through lab-based mock-ups and real-world testing campaigns in partnership with end users (e.g., EDF, CEA). XS-Ability directly targets Technology Readiness Level (TRL) progression by embedding safety and nuclearization requirements from the design phase onward.

The **DORADO** project (Benkrid et al. 2025) focuses on enabling the integration of digital tools, especially digital twins, into robotic decommissioning workflows through semantic interoperability and regulatory traceability. At its core, DORADO is developing a digital framework based on ontologies to formally structure knowledge across tools, actors, and assets involved in dismantling operations. This includes: (i) BIM-based mission control; (ii) linkage between digital twins and robotic mission planning systems; and (iii) standardised data models for knowledge transfer across decommissioning stages. The framework is designed to support explainable AI for safety-critical decisions and provide visual dashboards that enhance operator understanding and oversight.

8 CONCLUSIONS

Digital transformation is fundamentally reshaping the nuclear back-end, offering unprecedented opportunities to enhance safety, operational efficiency, and regulatory compliance through the integration of robotics, artificial intelligence (AI), and digital twin (DT) technologies. This paper has examined the strategic relevance of these innovations within the decommissioning and waste management domains, using the TECOP and Five Case Models to provide a structured analysis of their benefits and barriers.

While robotics extend operational reach in hazardous 5D environments, and DT/BIM systems improve simulation, training, and regulatory traceability, their deployment remains constrained by nuclearization requirements, fragmented certification processes, cybersecurity risks, and institutional inertia. These challenges must be systematically addressed to ensure scalable and sustainable adoption.

EU-funded initiatives such as **XS-Ability** and **DORADO** demonstrate the critical role of coordinated research in bridging the gap between technological development, field deployment, and regulatory integration. By targeting TRL advancement, semantic interoperability, and safety-

oriented design, these projects provide blueprints for future digital innovation in the nuclear sector.

Looking ahead, the successful digital transformation of the nuclear back-end will depend on sustained cross-sector collaboration, adaptive regulatory frameworks, and investments in digital infrastructure. Such efforts are essential to ensure the long-term safety, efficiency, and resilience of nuclear operations across Europe and beyond.

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