Deliverable 15.5: Digital Twins and their gaps in the Radioactive Waste Management domain

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Executive Summary

This Green Paper offers a comprehensive analysis of the current landscape, drivers, enabling technologies, regulatory context, and practical applications of digital twins (DTs) in the field of radioactive waste management (RWM), with insights drawn from both the nuclear sector and other industries.

Key Findings and Insights:

Definition and Role of Digital Twins: Digital twins are adaptive, data-driven virtual models that emulate the behavior of physical systems. They integrate real-time data and advanced simulations to support decision-making throughout the lifecycle of facilities and assets. In RWM, DTs are used to enhance cost efficiency, safety, regulatory compliance, lifecycle optimization, and knowledge preservation, leveraging technologies such as high-performance computing (HPC), artificial intelligence (AI), and the Industrial Internet of Things (IIoT).

Technological Foundations: DTs depend on the convergence of dense sensor networks (IIoT), big data architectures, AI/ML for modeling and anomaly detection, HPC for large-scale simulations, robust cybersecurity, and advanced visualization tools (including VR/AR). These technologies enable predictive maintenance, operational optimization, transparent stakeholder engagement, and improved long-term safety management.

Regulatory and Standardization Landscape: The regulatory environment for DTs in RWM is evolving, emphasizing safety, transparency, auditability, and data integrity. While nuclear-specific DT standards are not yet established, existing horizontal standards (e.g., ISO/IEC 30173, OGC, FAIR principles) and cybersecurity frameworks (NIS2, GDPR, IEC 62443) provide a foundation. Gaps remain in model certification, data quality validation, and integration with legacy systems, highlighting the need for pilot studies, cross-disciplinary collaboration, and ongoing engagement with regulators and standardization bodies.

Applications and Case Studies: DTs are being implemented for repository design, construction, operation, post-closure monitoring, predictive maintenance, training, and emergency response. Case studies demonstrate benefits in operational transparency, accelerated uncertainty quantification, and stakeholder communication, but also reveal challenges in model credibility, computational demand, and lifecycle integration. Cross-industry analysis underscores the importance of hybrid modeling, user-centric visualization, and robust data governance.

Challenges and Gaps: The main challenges include the lack of a unified DT definition for RWM, regulatory acceptance, integration with legacy systems, data management over long timescales, and the need for validated simulation models. Organizational change, cybersecurity, and sustainability over decades are also critical considerations.

Recommendations: The paper recommends adopting hybrid modeling (combining physics-based and AI/ML models), establishing governed data backbones aligned with FAIR principles, developing a nuclear-specific DT standards profile, institutionalizing model governance and validation, engineering security and traceability, and piloting high-value DT applications before scaling. Creating community benchmarks and fostering collaboration among stakeholders are essential for progress.

Conclusion: Digital twins represent a transformative approach for RWM and the nuclear sector, offering pathways to safer, more efficient, and transparent management of complex, long-lived systems. Realizing their full potential requires coordinated advances in technology, standardization, regulatory adaptation, and organizational change, supported by collaborative pilots and continuous improvement.

Keywords

Digital twin, Digital twins, Radioactive waste management, RWM, Gap analysis

Table of content

Glossary

3D / 4D	Two- / Three- / Four-Dimensional (4D often used as 3D + time)
AI	Artificial Intelligence
AR	Augmented Reality
ASME	American Society of Mechanical Engineers
BIM	Building Information Modelling
DITOCO2030	EURAD-2 Work Package "DITOCO2030" (project/work-package name)
DT / DTs	Digital Twin / Digital Twins
EC	European Commission
EU	European Union
EURAD / EURAD-2	European Partnership on Radioactive Waste Management (Phase 2)
EURATOM	European Atomic Energy Community
FE	Full-scale Emplacement (experiment at Mont Terri)
FAIR	Findable, Accessible, Interoperable, Reusable
GDPR	General Data Protection Regulation (EU)
GIS	Geographic Information System
HPC	High-Performance Computing
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
IIoT	Industrial Internet of Things
INSPIRE	Infrastructure for Spatial Information in the European Community (EU directive)
IoT	Internet of Things
ISO	International Organization for Standardization
KM	Knowledge Management
ML	Machine Learning
NEA	Nuclear Energy Agency
NIS2	EU Directive on Security of Network and Information Systems
NRC	U.S. Nuclear Regulatory Commission
OGC	Open Geospatial Consortium

OPC UA	Open Platform Communications — Unified Architecture
OT / IT	Operational Technology / Information Technology
PINN	Physics-Informed Neural Network
PREDIS	Pre-Disposal Management of Radioactive Waste
R&D	Research and Development
RWM	Radioactive Waste Management
SQL	Structured Query Language
THMC / THMC(B)	Thermal–Hydraulic–Mechanical–Chemical (–Biological) processes
UQ	Uncertainty Quantification
URL	Underground Research Laboratory (note: not a web address)
V&V	Verification and Validation
VR / XR	Virtual Reality / Extended Reality
WP	Work Package
XR	Extended Reality

1. Introduction

The digital twin (DT) concept has recently attracted attention also in radioactive waste management (RWM) as presented in the joint EURAD and PREDIS webinar (Schatz, 2022), by Jacques et al. (2023) and Kolditz et al. (2023). However, its current development and application, particularly in the field of radioactive waste disposal, are at an early stage as compared to other disciplines and industrial branches, such as the nuclear sector, manufacturing and healthcare. These first steps, which are undertaken in terms of the development of DT for concrete applications for the disposal of radioactive waste are described, for example, in Graebling et al. (2022), Pépin and Cotton (2023), Claps et al. (2024), Bertrand et al. (2024) and in the DITOCO2030 Milestone Document MS10 "Use Cases for Digital Twins in Radioactive Waste Management Facilities".

1.1 The Digital Twin concept

The digital twin concept might be different in different contexts (or applications) as each context requires own specificities for the digital twin (Semeraro et al., 2021). In the RWM domain, digital twins are tools to be used. As there doesn't exist one solution for a digital twin, several questions need to be answered:

1. What is the digital twin used for?
2. What size the digital twin is?
3. For whom is the digital twin made?
4. Who is using the digital twin?
5. Who is making the digital twin?

As a starting point, we refer to the summarizing definition by Semeraro et al. (2021). They analyzed 30 digital twin definitions published between 2002 and 2019 using formal concept analysis. From this, they identified five key aspects:

- Simulation along the product life cycle
- Synchronization between physical and digital objects
- Integration of real-time data
- Behavioral modeling
- Services provided by the digital twin

Their proposed objective is: "A set of adaptive models that emulate the behavior of a physical system in a virtual environment, using real-time data to update throughout its life cycle. The digital twin replicates the physical system to predict failures and opportunities for change. It prescribes real-time actions to optimize performance or mitigate unexpected events while observing and evaluating the operating profile."

1.2 Digital Twin Concept in Radioactive Waste Management

A digital twin is a dynamic, data-driven virtual representation of a physical system designed to simulate its behavior and evolution for evaluation, optimization, and prediction. While traditionally linked to real-time data from existing systems, in radioactive waste management—particularly deep geological repositories—the physical operational systems do not yet exist. Therefore, the concept must extend to hypothetical or planned systems, using the most complete data available at each lifecycle stage. Unlike simple digital replicas or simulation models, a true digital twin integrates relevant models and data to emulate functional and physical aspects, enabling adaptive behavior. Although bidirectional real-time data flows define classical digital twins, practical constraints in this domain often require manual or staged data integration. Subcategories such as digital models, shadows, and twins reflect varying levels of data exchange, emphasizing structured workflows over automation. This broader interpretation ensures digital twins remain a powerful tool for design, safety, and lifecycle management in complex, long-term projects.

1.3 Methodology for the green paper production

The research methodology for the DITOCO2030 project green paper followed a structured, evidence-based, and participatory approach. The process began with problem definition and scoping, where the research team clarified the objectives, thematic boundaries, and key questions to be addressed, which were outlined in the project proposal and workplan. The process of the green paper production began with the definition of an initial table of contents, which served as the structural foundation for the document. To capture early input, an online survey was conducted among initial contributors to express their interests and suggest topics aligned with the proposed additional sections. Key thematic areas included current practices of digital twins and gap analyses, ensuring that the paper addressed both the state of the art and existing challenges. To guide contributions, short example sections were incorporated into the draft document, providing clarity on the expected format and depth. All project partners were actively encouraged to contribute, with an open and flexible approach that allowed freedom and overlapping of content, avoiding restrictive guidelines. Sources for contributions included academic literature, example projects, and company best practices, ensuring a diverse and evidence-based foundation. The resulting draft contribution document was designed to act as a reference library, serving as the primary source material for the final green paper. Collected contributions were much larger than can be included in this green paper. The draft contribution document is serving also as a supporting source of the upcoming state of the art document and a white paper to be produced in DITOCO2030.

2. Drivers for the Digital Twins in the radioactive waste domain

The implementation of digital twins (DTs) across the lifecycle of radioactive waste facilities is propelled by multiple interconnected factors. **Cost and efficiency gains** arise from predictive maintenance, virtual prototyping, and workflow optimization, reducing downtime and lifecycle costs. **Safety and risk mitigation** is enhanced through continuous monitoring, accident scenario modeling, and decision-support tools that minimize human exposure in hazardous environments. **Regulatory compliance and transparency** benefit from auditable simulations and clear data flows, strengthening safety cases and fostering stakeholder trust. DTs also enable **long-term structural health management**, forecasting degradation and guiding refurbishment strategies to ensure repository integrity over decades. Through **lifecycle optimization**, real-time data integration and multi-physics simulations improve planning, anomaly detection, and performance assessment from design to closure. Furthermore, DTs support **knowledge preservation and data integration**, consolidating diverse geological, thermal, and chemical datasets to maintain digital continuity and institutional memory. Finally, **technological enablers**—including HPC, AI, IoT sensors, and immersive visualization—expand DT capabilities for real-time assimilation, uncertainty quantification, and stakeholder engagement. While benefits include decision support, accelerated analysis, and enhanced communication, challenges remain in model credibility, computational demand, and sustaining integration over decades.

3. GAP analysis

3.1 Definition

The definition of DT will always be domain-specific. However, there is no common definition of a DT available, as analysed by Jones et al. (2020) and Semeraro et al. (2021), for example, which could be directly adopted to this specific domain of radioactive waste disposal despite the ongoing standardisation effort (ISO/IEC 30173, 2023). This results in diverse interpretations of this technology by different disciplines, leading to the risk of not understanding and exploiting its maximum potential, as underlined by Winkler et al. (2020) and Wright and Davidson (2020). Exemplarily, there are different realisations of twinning processes practiced (both physical-to-virtual and virtual-to-physical connections versus solely physical-to-virtual connection), with differently perceived roles of human being/ automation in this process, as identified by Jones et al. (2020). Furthermore, in some cases a DT is applied to very specific phases of a life cycle (e.g. operational or maintenance phases) due to its very specific use case. This is, however, contradictory to the concept by Grieves and Vickers (2017), in which a DT continually evolves over its entire life cycle, beginning with a DT prototype. Moreover, there are other concepts such as digital models, digital shadows or virtual twins in addition to DTs, which relate to different digitalisation levels (see e.g. Winkler et al., 2020).

This has resulted in the need for the establishment of a common DT definition, based on a common understanding of capabilities and added values of this technology, which would reflect the peculiarities and requirements originating from radioactive waste disposal. Such specificity is diversity, availability/maturity of the physical asset to be twinned (e.g. the repository itself) in the subsequent phases of a radioactive waste disposal programme or at least its (partial) representation by an underground research laboratory with corresponding experiments and longetivity of radioactive waste management programme.

3.2 Digital Twins in radioactive waste management

The spectrum of possible applications of a DT over the different phases of a radioactive waste disposal programme is very broad. On a general level, one can say the DT applications are related to quantitatively synthesize all knowledge to support operational decision making (including the exploration and exploitation of resources, as well as governance considerations (sustainability, risk) (Chassagne and Wellmann, 2023). Many potential applications emerged during the discussions in DITOCO2030 and a non-exhaustive list based on these discussions is given below.

<u>Planning - Licensing process - Safety</u>

- Safety
  - Safety management
  - Emergency response
- To support future decisions on the progressive development of a facility
  - Formulate functional requirements / safety requirements
  - Compliance with functional requirements / safety requirments
- Operational transparency to stakeholders thus working as a visualization and communication tool.

<u>Construction and Operational phase</u>

- Demonstration that disposal and geological environment remain within expected evolution and the phenomenology operating range within the context of the safety assesment
- Demonstration of retrievability of waste packages
- Ageing management
  - Maintenance
  - Predictive diagnostics
  - Anomaly detection
- A training tool by a virtual reality environment

The potential applications depend on aspects such as the physical asset to be twinned, the function of the DT and the expectations of the stakeholders concerned. The physical asset can cover any physical object or process related to an arbitrary spatial and temporal scale, ranging from a single repository component or subsystem, through machines and systems together with related specific construction and operational processes, to an underground research laboratory with corresponding experiments, up to the entire repository system. Despite its importance, the development of a DT for machines and systems, employed in construction and operational phases, is not yet the topic of discussions on DT applications in the existing literature (e.g. Kolditz et al., 2023; Jacques et al., 2023). This application aspect is, however, recognised by WMOs as being relevant for virtual commissioning and predictive maintenance (Jones et al., 2020; Winkler et al., 2020; VDMA, 2020; Attaran and Celik, 2023; ISO/IEC 30173, 2023), also from the perspective of the robotisation, automation and remote-controlling of construction and operational processes in radioactive waste disposal within the framework of Industry 4.0.

Considering the wide range of DT applications, a roadmap supporting a strategic implementation of the DT technology in the different phases of a radioactive waste disposal programme is required, in order to identify the use cases for which the full potential of this technology can be exploited. The roadmap should recommend function-specific DT applications in each phase of a radioactive waste disposal programme, highlight the relevance of DT-related technologies as well as outline the necessary steps in terms of the development of a DT. The DT applications identified in the roadmap should reflect the motivation of the WMOs behind the introduction of this technology, which is driven primarily by the increase of confidence in terms of safety and work efficiency, as well as in the feasibility and maturity of technological solutions. To achieve a solid, reasonable basis for justification of the DT utilisation, a cost-benefit analysis of specific DT use cases is necessary, which was also pointed out by Jones et al. (2020) and Winkler et al. (2020) (see also next section). This analysis should be supported by a general discussion regarding the advantages and disadvantages of this technology, including comparisons to the use of classical and other (modelling) methods and technologies.

3.3 Functionality – architecture

A digital twin works in an unified digital environment. Here is an extended list of potential components of digital twins based on the background work done:

- Physical system
  - Hypothetical
  - planned
  - exising
- Digital system
- Connections
  - Integrated data flow from the physical to the digital system
  - Integrated data flow from the digital to the physcial system
- Data
  - Preparation
  - Data analysis (data-driven models)
  - Data Management (storage, archiving, provenance)
- Model – Computation - Dynamic modelling
  - Integrated THMC(-B) models
- Visualization
  - BIM
  - Geo-Models
  - Virtual reality / virtual augmentation
- Decision-support tool/component - accounting also for uncertainties across the entire integration chain

In order to facilitate this complex development work, it is necessary to establish guidance for DT conceptualisation and design, including a specification of requirements, tailored to the needs of radioactive waste disposal and those of WMOs, as the latter are responsible for the programme implementation. An appropriate design approach and IT infrastructure is required to take into account the dynamic as well as time-evolving and refining nature of DTs upon real-time data generation over the subsequent programme phases, representing different physical assets and fulfilling different functions. Stepwise, standardised and interdisciplinary DT development, incorporating a holistic view and interoperability, is thus essential. The appropriate and effective manner of the structuring and management of a DT system (including the definition of standardised and quality-assured workflows) should be addressed, since a number of different options seem to be possible, such as a set of complementary, interdependent local DTs (Pépin and Cotton, 2023), a modular DT (Schatz, 2022) or a DT-based platform envisioned in WP DITOCO2030. Moreover, it is necessary to specify the overall requirements for IT system architecture, particularly those that are important from the perspective of long-term usability, for example flexibility and extensibility for any other future applications or innovative software developments, robustness and cross-company collaboration. With respect to the latter, the development of a collaborative platform with properly defined user interfaces is very important for effective collaborative work of different disciplines and company intersections.

3.4 Regulatory aspects – Acceptance aspects – Social-economic aspects

The adaptation of digital twin technology in the nuclear sector (including decommissioning activities and waste management) offers several advantages. However, because the nuclear facilities operate in highly regulated environments (safety/security and public/environment protection) the adoption of a novel (emerging) technology such as digital is often viewed as a disruptive technology and thus issues might exist related to the acceptance of these technologies for their application to safety-related issues by stakeholders, including Waste Management Organisations (WMOs), regulators and civil society (Winkler et al., 2020). EURAD-1 WP UMAN also discussed the latter, using an example of uncertainties related to “new” knowledge in the context of overarching uncertainties concerning human aspects (Haverkate et al., 2024). In these discussions, a challenge of choosing between well-proven, state-of-the-art technologies and new technologies potentially promising better solutions was identified by WMOs.

The integration of digital twin technology can represent a huge shift in the operational practices: for example long established procedures and practicies might need to be reviewed or even updated (need for change of mindset). Additionally, nuclear regulations have evolved slowly over time and are typically quite conservative. Since (usually) emerging technologies are not anticipated within these existing regulatory frameworks, their introduction creates uncertainty, sense of further insight, case studies / validation but also calls for new regulatory adaptations/interpretations. The nuclear sector will need to balance the benefits of any emerging technology, including digital twins, with its potential risks and the regulatory and cultural challenges it presents.

There are significant gaps in the current regulatory framework when it comes to the application of emerging technologies like digital twins in nuclear facilities. Explicit regulations or guidelines governing the employment of DTs in national programmes are currently missing. These gaps include areas related to data integrity, model certification, integration with legacy systems, and cybersecurity, all of which are critical for safe and effective implementation.

The integration of digital twins in nuclear operations requires a comprehensive, holistic approach that not only addresses the technological aspects but also considers operator training, emergency preparedness, cybersecurity, and environmental impact. Regulatory adaptations must encompass all of these dimensions to ensure the technology is implemented safely and ethically.

Data integrity

Digital twins rely on inputs from connected systems/sensors for real time monitoring and/or simulations. Linked with this is requirement of data retention and readability over multiple decades. An important gap is a lack of established standards for validating the data quality and integrity used by digital twin models in the nuclear sector. National and international regulatory agencies (ISO/IEC) and their standards need to be integrated.

Model certification

As with data, certification and validation of digital models and underlying mathematical and numerical models are required following national and international accepted standards (ISO). There is no formal regulatory process for validating & certifying digital models used in the nuclear sector, creating a gap in trust and regulatory acceptance.

Cybersecurity

There is an increased vulnerability to attacks and data manipulation due to interconnectivity. Digital twin technoloy is deemed a disruptive technology; there is no clear regulatory guidance on mitigating these risks in the nuclear context

Compliance with above aspects (e.g. data integrity, model certification, cybersecurity) will require audits by national and/or international bodies (such as NRC, IAEA, ONR). On the other hand, data of the digital twin (real-time data, digital records of operations, etc.) can be used. There is a lack of clear guidelines on how digital twin data should be used in regulatory audits or inspections.

Socio-economic and organizational aspects

Overall, there are several organizational challenges which might also require structural changes – aspects are also linked to the integration with existing (legacy) systems and the need to redefine internal processes, workflow and decision-making procedures. Digital twin technology rely on components from the commercial sector; these components should also be usable within the nuclear sector and radioactive waste management. Therefore, the available technology or technology to be developed are also tied to economic feasibility, investment requirements, and potential returns. The vendors landscape is still emerging but adaptation of the already available experience and standards from other disciplines might be limited due to specific requirements posed by the nuclear sector. There is a need for trusted providers with nuclear sector experience with the underlying challenge that many developers usually are linked to other industries (e.g. construction). There is a limited understanding and/or high uncertainty on the long term financial benifits to be expected from the nuclear sector in general, and long-term radioactive waste managment specifically which influence how quickly and effectively DT can be implemented in this sector.

Therefore, the demonstration of DT effectiveness, robustness and reliability (including its verification and validation) by case studies, information exchange and collaboration in pilot experiments can help to provide trust in the digital technology both related to the required efforts for organizational aspects (and thus ensure the engagement of facility leaders and system operators) of digital twin technology implementation, and for the reducing risks of financial investment in digital twin technology development. As one potential benefit of digital twin technology in radioactive waste management is increasing public trust in facility operation, case studies are also inevitable to win that trust. It is important to foster close cooperation between regulators and vendors/site owners to address these issues, and highlight this existing partnership when engaging with the public. The following actions will contribute to ensure that digital twins are not only technically robust but also collaborative, transparent, and impactful—paving the way for safer, more sustainable RWM research and innovation:

- Convene a cross-disciplinary IT experts working group to develop and enforce standardisation guidelines in close link with KM work package.
- Pilot standardised digital twin prototypes in select research areas to validate the framework.
- Engage with international standardisation bodies (e.g., ISO, IEC, or the Nuclear Energy Agency (NEA)) to align efforts with global best practices.
- Establish a continuous improvement mechanism, incorporating feedback from stakeholders to refine standards over time

3.5 Data

Data Management – Handling of "Big Data"

The volume and frequency of data do not match traditional Big Data definitions; however, the level of variety, contextual complexity, and duration involved still calls for similar data architectures and processing strategies. The Big Data related to radioactive waste management, specifically of radioactive waste repositories, can be described as a multiphysics data system that is contextualized and structured, with strong semantic and metrological components, relying on spatial modeling tools and data science techniques.

Long Term Operation / Long Term Evolution

Digital twins aid system evolution by monitoring degradation, simulating refurbishment strategies, and verifying upgrades. Ageing management programs are crucial for ensuring the safe and reliable operation of systems. DT could be aligned with the potential very long-term life cycles in radioactive waste management including managmenet of asset history records and life cyle management tools are required.

Data Collection - Quality – Standardization

Adequate real-time data acquisition, management and processing will play important roles in terms of the combination of different types of data originating from multiple sources (e.g. experiments, monitoring, simulation results) and heterogeneous objects (Kolditz et al., 2023). It undoubtly will require centralization, scalablity and a sustainable database architecture with handling heterogeneous data streams. A framework for database architecture should be taken into account: (i) modular design principles, allowing for incremental updates and compatibility with emerging technologies (e.g., cloud computing, edge analytics), (ii) the principles of FAIR (Findable, Accessible, Interoperable, Reusable) data principles, ensuring that datasets are well-documented, version-controlled, and accessible to authorised stakeholders, and (iii) robust data governance protocols, including role-based access controls, audit trails, and compliance with GDPR and EURATOM regulations to address confidentiality and security concerns.

Data management should follow the FAIR principle. This is also related to data integrity. The determination of required input data types, their sampling ratios and connections, approaches for the meaningful reduction of acquired data as well as output information play a crucial role for optimal DT management effort and performance (Winkler et al., 2020). It will also contribute to the necessary standardisation of knowledge representation through further development of ontology associated with the radioactive waste domain. This harmonisation should extend to metadata standards, such as those proposed by the ISO 19115 or INSPIRE directives, to facilitate automated data validation, integration, and reuse. From the perspective of a DT application, also the establishment of a long-term monitoring strategy and programme, including specifications of parameters to be measured and the development of corresponding sensors, will be necessary, as identified by EURAD-1 WP MODATS (Schatz, 2022).

3.6 Modelling - Behaviour

Representation of physcal systems

Another challenge associated with development of a DT for a repository results from ensuring the correct representation and setting of the underground engineering structures in a geological environment. This requires a combination of geological, hydrogeological, geochemical and geotechnical concepts, models and data via a geographic information system (GIS) and those related to building information modelling (BIM) as well as the coupling of BIM with numerical solvers for the physical modelling of repository components to facilitate the optimisation of the repository design (Jacques et al., 2023; Kolditz et al., 2023). Considering geological systems, further difficulties are posed by the complexity of geological structures, strong coupling of THMC(B) processes as well as uncertainties at different spatial and temporal scales.

Simulation capabilities

From a regulatory point of view, there is a need for validated simulation models covering radwaste evolution; in addition, this is also the case for system scenarios. This is a prerequisite for confidence in models used in design and safety in digital twins. From a scientific point, there is a lack of validated physics-based models for all possible failure modes and we have to consider also the limitation that full 3D THMC repository evolution simulations cannot be currently performed.

High Performance computing (HPC)

Modelling the behaviour and evolution of the physical system is extremely challinging specifically since digital twins should include a high degree of realism. For example, In the case of realistic repository scale simulators complex and fully coupled THMC processes evolving over a period of several hundreds of years need to be resolved. The solution of these processes in 3D and at high resolution, in order to account for local heterogeneities, requires the solution of coupled non-linear differential equations at fine temporal resolution. HPC enables the integration of such models in digital twin workflows especially when physical modelling results are needed in real-time for supporting the design, optimization and decisions. In the absence of HPC capabilities the digital twin technology has to rely on simplified low resolution approximations which might miss critical aspects and dependencies of the system evolution.

At the same time, HPC is also essential for sensitivity analysis and uncertainty quantification which typically requires several thousands of model implementations and simulations. This allows to adapt the models on-the-fly and can serve the purpose of predicting possible outcomes before they occur. The parallel execution of such simulations is key enabling technology. Moreover, the application of machine learning and AI techniques as part of the digital twin workflows, also requires high performance computing. This is needed for the processing of the resutling big data (e.g. from sensors or from computer simulations) and for the training of the ML models.

Model codes and architecture should be adapted to be able to run on newest developments in computing infrastructure. Contemporary HPC systems are no longer characterised by homogeneous clusters of identical CPUs. Instead, they are heterogeneous architectures combining multi-core CPUs, GPUs, and other accelerators. It is reasonable to hypothesise that these trends will continue to intensify in the future. A fundamental challenge in the realm of HPC code development pertains to the delicate trade-off between portability and performance. From a scientific standpoint, it is imperative that software designed for use in the field of scientific research remains compatible with a range of supercomputers across the globe. Conversely, attaining peak efficiency frequently necessitates hardware-specific tuning. In the context of substantial legacy applications, the financial implications of attaining both portability and performance can be substantial. The process of scaling numerical codes from thousands to millions of cores introduces challenges in terms of parallel efficiency and fault tolerance. The models in a digital twin should be able to handle major paradigm shifts in the HPC architecture at a 10-year timescale. Although the changes in HPC architecture opens up the frontiers for the model realism, it also put great challenges in porting the existing models.

AI and ML

Large scale-models (concerning the domains of time, space and complexity) will generate vey high computational costs. Thus acceleration utilizing AI tools such as machine learning are a promising strategy. However, this might also be seen as disruptive technology for which case studies are required to illustrate that AI – ML integration in models in digital twins within the radioactive waste domain are effectively accelerating simulation models and produce results with high accuracy and confidence.

3.7 Visualization – extended reality - Transparency

Tools must support a wide range of data types of different dimensionality and in different formats. These include points, lines, polygons and 3D meshes in vector formats, which can represent sensor measurements, map boundaries, areas and models of underground structures. They can also encode scalar, vector and higher-dimensional raster data, such as elevation models or process simulations (Demir et al., 2022). Many such tools have long existed for two-dimensional datasets in the form of desktop or browser-based GIS applications, and software libraries for integration into a geosystem digital twin are readily available (e.g. QGIS, MapLibre and OpenLayers). Existing tools for three-dimensional and higher-dimensional data tend to be more generic (e.g. ParaView, VTK and three.js), and common rendering techniques for volumetric datasets are less suited to a geospatial context.

A key challenge in this context is integrating available tools and techniques into software that enables users to interactively explore the digital twin's contents and draw conclusions from them. Potential users and beneficiaries of a geosystem digital twin include researchers, decision makers, students and the general public, who have varying levels of domain and technical expertise. It is therefore crucial to design the system so that it is user-friendly and accessible. For example, this can be achieved by eliminating the need for specialised software through browser-based solutions, and by selecting visualisation techniques and colour schemes with which users are familiar (Graebling et al., 2022, 2024; Ziefle et al., 2022). At the same time, visualisation tools should provide a foundation for further scientific work by offering access to raw datasets and their metadata, as well as options for data assessment and verification, to ensure the numerical and scientific accuracy of the provided analysis tools. The active involvement of different user groups in the design process is crucial to achieving these goals (Kolditz et al., 2023; Lehmann et al., 2024).

Extended reality enables complex and large amounts of data to be visually combined with their geological and geographical real-world context. This offers significant potential for the integration of comprehensive data and models, which is an essential element in DT concepts. XR for geo-applications enables actual data and predictions to be blended with the real-world context, providing a holistic view of facilities in the past and future. For repositories (and also underground research facilities), there is a need to develop and harmonise XR concepts for various repositories/URLs across Europe, in order to support an overarching DT concept. Furthermore, XR capabilities are required in other geotechnical application areas, such as geothermal energy systems (Rink et al., 2022). Therefore, generalised XR concepts and software tools would greatly benefit various geoscientific application areas.

Transparency is paramount in RWM research, where decisions carry significant safety, environmental, and societal implications. By embedding transparency into the digital twin framework, it enhances accountability, facilitate regulatory compliance, and strengthen public confidence in its research outcomes. Important aspects are:

- Standardised data-sharing protocols, such as ODbL (Open Database License) or CC-BY-SA (Creative Commons Attribution-ShareAlike), to clarify usage rights and obligations.
- Automated data provenance tracking, leveraging blockchain or distributed ledger technologies to ensure immutability and traceability of data lineage.
- Stakeholder-specific dashboards, providing tailored visualisations and reports to meet the informational needs of different audiences (e.g., technical summaries for engineers, high-level insights for policymakers).

3.8 The need for a benchmark

An important step would be the development of a benchmark or case study that can address different challenges both from a technical aspect but also from a strategic and economic-social point of view. By addressing the challenges of data harmonisation, database architecture, IT tool selection, transparency, and visualisation, this can establish a cohesive, high-performance, and future-ready digital twin ecosystem. This will not only accelerate innovation in nuclear safety and waste management but also set a global benchmark for digital twin applications in complex, safety-critical industries.

4. Conclusions

This Green Paper consolidates the state of practice, technical enablers, regulatory posture, and gaps for applying digital twins (DTs) across radioactive-waste management (RWM) and related nuclear domains. The evidence gathered indicates that DTs, conceived as adaptive, model-driven representations that integrate data flows, physics-based simulation, and (where useful) AI/ML surrogates, can materially improve operational transparency, safety assurance, and lifecycle efficiency. However, real-world deployment in RWM remains early-stage compared with adjacent sectors; success depends on deliberate investment in data foundations, hybrid modelling, standardisation, and compliance-grade governance from the outset.

4.1 What Digital Twins mean in RWM

This document adopts a pragmatic view of DT taxonomy—digital model → digital shadow → digital twin, and, for planned systems, a "physical shadow"—decoupling value from strictly automated bidirectional flows and focusing instead on well-defined data workflows and pipelines. For repositories, bidirectional control is limited (particularly post-closure); nevertheless, DTs remain valuable as offline/virtual twins for forecasting, uncertainty analysis, and safety-case communication. DTs should be as realistic as purpose requires (geometry, processes, uncertainties) and engineered as living systems with traceable updates across the programme lifecycle.

4.2 Demonstrated value, what the cases collectively show

- Operating-phase repository support: Multi-physical DTs (e.g., Cigéo) integrate BIM/CAD, geology, and THMC simulation with data assimilation to verify that observed evolution stays within expected envelopes (including retrievability constraints).
- URL-centred integration & communication: At Mont Terri, DTs function as virtual experiment systems and immersive VR environments for planning, uncertainty visualisation, and stakeholder dialogue, backed by open-source multi-physics toolchains.
- Hybrid modelling for tractability: In the FE experiment, high-resolution heat-transport models are coupled with ML surrogates to estimate latent states (e.g., saturation), achieving high predictive accuracy and automatic sensor-quality checks.
- Predisposal integrity analytics: For cemented waste drums, neural-network surrogates compress million-case sensitivity analyses from weeks to seconds (porosity, gas, pH, ion evolution), enabling risk-informed screening.

Conclusion: RWM DTs are credible as decision-support systems that combine heterogeneous evidence, propagate uncertainty, and shorten analysis cycles, provided their data lineage, model credibility, and assumptions are explicit and auditable.

4.3 Technical foundations that consistently matter

IIoT & robotics as the data plane: Radiation-hardened fixed sensors plus mobile nodes (robots as roaming gateways) feed authenticated, time-stamped telemetry (OPC UA/MQTT/Modbus) into governed platforms; edge processing filters, fuses, and prioritises streams.

Big-data practice tuned to longevity: Although volumes are moderate, variety, context, and decades-long traceability dominate. Use hierarchical binary formats (HDF5/NetCDF) for primary arrays, SQL cores for integrity and lifecycle provenance (ISO/IEC 11179), and analytical spaces (columnar/matrix/graph) for ML/UQ. Treat metrology and uncertainty as first-class data.

Hybrid physics + AI/ML: Physics preserves invariants; surrogates/PINNs/ROMs deliver speed for assimilation, UQ, and "what-if" studies. Combine with Gaussian-process regularisation, graph neural networks for sensor integrity, and compact vision models for inspection where applicable.

HPC as a design constraint: Repository-scale 3D THMC and ensemble UQ require heterogeneous CPU/GPU nodes and portable kernels; expect strong-scaling limits, load-balancing challenges, and the portability vs performance trade-off over 10-year hardware cycles.

XR-ready visualisation: Browser-first GIS plus 3D/volumetric stacks (QGIS/MapLibre ↔ VTK/ParaView/three.js) and VR deliver interpretable, uncertainty-aware views for engineers, regulators, and the public—without hiding raw data or metadata.

4.4 Regulatory acceptance, credible but incomplete

Regulators seek safety, transparency, and auditability, not novelty. Current frameworks emphasise model V&V, uncertainty quantification, configuration control, and record integrity, but there is no universal acceptance path for DT evidence, no standard model-certification process (particularly for ML surrogates), and limited guidance on using DT outputs in audits/inspections. Cybersecurity expectations (e.g., NIS2, GDPR, IEC 62443) apply end-to-end, including third-party risk. Early, structured engagement and pilot-based evidence remain essential.

4.5 Standardisation, usable base exists, nuclear profile needed

A robust horizontal base (e.g., ISO/IEC 30173 for DT concepts; OGC SensorThings/OMS for observations; ISO 19115/INSPIRE for geospatial metadata; ASME V&V 40 for model credibility) is applicable today. The field still lacks nuclear-specific DT standards, arguing for a DT Standards Profile that selects and constrains existing norms for RWM use (data schemas, interfaces, governance, visual encodings).

4.6 Cross-cutting risks and constraints

Legacy integration & organisational change: Brownfield OT/IT heterogeneity and entrenched procedures are non-trivial adoption barriers; deterministic interfaces and change-managed workflows are required.

Cybersecurity & supply chain: Interconnected DTs widen attack surfaces; verifiable telemetry, signed artifacts, zero-trust segmentation, and supplier assurance are non-negotiable.

Sustainability over decades: Data/media migration, model re-validation on updates, and software sustainability (modularity, CI/testing, documentation) guard against obsolescence and staff turnover.

4.7 Recommendations for Digital Twins development steps

Adopt hybrid modelling as the default: pair first-principles THMC models with targeted surrogates to enable frequent assimilation and UQ without sacrificing interpretability.

Set up a governed data backbone early: FAIR-aligned schemas, geospatial/BIM alignment, append-only provenance, quality flags and calibration histories as mandatory metadata.

Publish an RWM DT Standards Profile: consolidate ISO/IEC, OGC, GIS/BIM, cybersecurity, and model-credibility norms into a profile used for procurement and inter-partner integration.

Institutionalise model governance and V&V: define promotion stages (dev → qual → regulated use), benchmark cases, and re-validation triggers for both physics and ML components.

Maintain a database of tests agreeded by the End-Users for models' validation and a set of analytical and numerical solutions agreed also by the End-Users to be used for computer codes' verification.

Engineer security and traceability as first-class properties: mTLS for ingestion, signed models/meshes/binaries, zero-trust segmentation, third-party due diligence, and incident playbooks aligned with NIS2/GDPR/IEC 62443.

Pilot to platform—prove, then scale: select 2–3 high-value pilots (e.g., thermal evolution around emplacements; predisposal package integrity; URL transparency with VR), quantify benefits, and promote reusable components into a shared platform.

Create a community benchmark: a reference case spanning data ingestion, THMC modelling, surrogate training, UQ, and regulator-style reporting to anchor V&V and comparability across tools and partners.

4.8 Outlook

Digital twins are technically feasible and strategically relevant for RWM. Their distinguishing advantage is not a single algorithm but the systemic coupling of trustworthy data, verifiable physics, targeted AI acceleration, and interpretable visual analytics—delivered under standards-based governance that can withstand regulatory scrutiny over decades. The path forward is clear: consolidate foundations (data, governance, standards), demonstrate value with pilots, and institutionalise DT capabilities as a shared platform and operating practice rather than a collection of point solutions.

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