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European collaborations for safe and efficient dismantling: digital twins, ontology and data exchange

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Abstract. Due to economic considerations and political decisions, an increasing number of nuclear facilities is to be dismantled in the coming decades. The large number of nuclear decommissioning projects must comply with the reliability and safety requirements in order to make the dismantling operations more efficient, safer and more cost-effective.

This paper gives an overview of European coordinated efforts to develop and demonstrate the use of digital tools and methods for safe and efficient decommissioning activities through the projects PLEIADES (PLatform based on Emerging and Interoperable Applications for enhanced Decommissioning processES) and DORADO (Digital twins and Ontology for Robot Assisted Decommissioning Operations).

Achieved by the end of 2023, the PLEIADES project defined a common ontology specifically designed for nuclear decommissioning projects. It developed a central server for combining data while ensuring compatibility and it provided the first pilot integration of digital decommissioning and waste management support tools. PLEIADES demonstrated the usefulness and efficiency of this concept using data of three real nuclear sites.

Starting in the second half of 2024, the DORADO project will continue this work by creating a holistic digital data-driven platform as a BIM/DT (Building-Information-Model/Digital-Twin) and by integrating new digital tools into a coherent suite customized for decommissioning applications. Eight digital technologies will be integrated, including point-cloud data, 3D models and change detection, sensors data fusion, ALARA (As Low as Reasonably Achievable) dose estimation, robot mission optimization, and smart voice assistant interface.

1 Introduction: dismantling context and expectations

Activities related to Decommissioning and Dismantling (D&D) of nuclear facilities are currently on the rise and will continue to increase in the coming years worldwide. As these scenarios were not foreseen during the design and construction – several decades ago –, they are very challenging and research is needed to look for their feasibility and optimization.

In this context, the European Commission (EC) funded the project PLEIADES (PLatform based on Emerging and Interoperable Applications for enhanced Decommissioning processES) and is currently funding the project DORADO (Digital twins and Ontology for Robot Assisted Decommissioning Operations) in order to improve safety and efficiency by applying several digital technologies such as Artificial Intelligence (AI) and Building Information Modelling (BIM).

Main expected impacts of the DORADO project are to increase the efficiency, safety, and cost-effectiveness through the integration of advanced digital technologies and robotics. It will significantly reduce human exposure to radiation, improve decision-making processes, and optimize resource allocation throughout the decommissioning lifecycle. Safety is also enhanced by reducing the risk of misunderstandings and confusion when working in high-risk controlled area and will be valuable in training use. Having a BIM model integrating data from various sources with properly defined ontology enables remote planning, training and inspection activities.

Using both the dedicated decommissioning ontology and data transfer protocol that were previously created

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in PLEIADES, the DORADO project will create a platform that combines BIM, digital twins, and point cloud technology. The project will address the identification of the users' needs, conceptual design, system design and implementation, demonstration on real use cases, exploitation and standardization. After completion, the platform should be used especially for: characterization and sampling, clearance of surfaces and structures, cost estimation, in situ waste characterization, knowledge management, risk identification, etc.

A key feature is a comprehensive ontology that improves data sharing between different digital tools. Ontology development will continue from the basis developed in the PLEAIDES project throughout the whole DORADO project period, especially focusing on standardizing and ensuring compatibility with higher-level international development within IAEA and EC.

2 First steps in PLEIADES

The PLEIADES project [1] occurred between October 2020 and November 2023 and aimed at providing a digital environment making decommissioning activities more efficient and safer. PLEIADES relied on an innovative digital decommissioning approach inspired by the BIM (Building Information Modelling) methodology.

PLEIADES has created a new digital methodology to improve nuclear decommissioning and has developed a system to demonstrate how a BIM-like model and connected digital tools can help decommissioning activities by improving safety, minimising radiation exposure and optimising costs. It has also contributed to facilitating higher standardization required for international applications.

The results of the PLEIADES project can be divided into several groups:

- development of the first version of a dedicated decommissioning ontology.
- Development of the first version of the dedicated data transfer protocol based on this ontology.
- Development of the digital platform using previously developed ontology and data transfer protocol.
- Demonstration of the results on real use cases with data from 3 nuclear sites.

The achieved results showed that the concept of digital platform, capable of connecting different software tools together, improves the efficiency of data transfer between these tools, which in turn, has impact in the increase of the efficiency of the planning activities.

It has also been recognized that a small number of real use cases for which the concept of digital platform has been demonstrated limited the flexibility and technical readiness level (TRL) of the first version of such a platform. For this reason, it has been recommended at the end of the PLEAIDES project to continue with the development of both the dedicated ontology and data transfer protocols and demonstrate this concept in a new set of real use cases.

3 Continuation in DORADO

The PLEIADES project resulted in a digital platform, as the first step of tool integration. After use cases demonstrations, some recommended next steps were:

- extend the coverage of the supported ontology and the supported decom planning activities, ensuring also compatibility with international standards, e.g. [2].
- Integrate more technologies, such as AI, robotics and sensor networks.
- Promote the concept for wider use.

Consequently, after the success of PLEIADES, the EC funded the project DORADO [3] with the participation of some of the previous partners and new ones.

DORADO will integrate new technologies into the server. Altogether, eight technologies will be researched and integrated into the platform. Some of these are discussed in more detail in Section 4.

1. Sensor data fusion with temporal dimension.
2. Environment data comparison against BIM (validation of the BIM model).
3. Point-cloud and 3D model change detection (similar as previous point., but aimed for regular updating of the model).
4. Digital twins based ALARA dose estimation.
5. Server-based integration with IFC (Industry Foundation Classes) file format and extended data queries.
6. Mission control, robot route optimization.
7. Human to System smart voice assistant interface.
8. Standardization using the common ontology.

4 Technological developments

4.1 BIM-like concept development

The idea is to inspire from the BIM (Building Information Modelling) concept, which enables all the information related to the construction of a new building or infrastructure to be managed and visualized in the form of a 3D model. PLEIADES adapted this concept to the dismantling of a nuclear installation, gathering in a BIM-like model all the useful data: building geometrical and composition information, as well as all radiological data and necessary information for demonstrating the use of this concept in few use cases.

The concept was demonstrated in simulation scenarios for: improving safety, minimising radiation exposure, optimising costs and schedules, and carrying out the work.

The use of 3D modelling and simulation is a method already being widely used, although very often only for specific use cases. PLEIADES demonstrated the use of the same approach (based on the ontology and the server described hereafter) for various cases:

- comparison of results obtained (especially regarding workers dose exposure) between manual and remote interventions for radiological characterization.
- Evaluation of the benefits of 3D data and BIM data for a large equipment cutting and its evacuation scenario.

- Comparison between manual and automated decontamination of building surfaces.
- Strategic risk management planning.
- Providing a regulatory review process based on simulated scenarios concerning activities feasibility, risks, safety, etc..
- Waste management planning with: material composition and radiological state consideration, waste treatments techniques comparison and costs evaluation.

4.2 Common ontology

An ontology [5] is a collection of concepts and the underlying properties that connect these concepts. PLEIADES has defined an ontology specifically designed to represent nuclear decommissioning projects.

The software tools being integrated into PLEIADES already existed and had their own terms, concepts and history. This required the development of a common understanding, as direct interfaces were difficult to establish. In the PLEIADES project, a common ontology (see Fig. 1) was defined to achieve a common platform for existing software for 3D and BIM in decommissioning. The approach of this development was to use what was available, to obtain a simultaneous top-down and bottom-up approach and to define a decommissioning core that covers specific parts [6].

There is an on-going focus on establishing a common ontology between the IAEA (International Atomic Energy Agency) and the EC-JRC (European Commission – Joint Research Centre). This ontology will allow standardized access to the respective knowledge repositories (i.e. the INIS database or the IAEA Nuclear Wiki). The further development of the ontology in the DORADO project and the approaches within IAEA and EC-JRC will be aligned (by participation in working groups and exchange of information) to ensure compatibility. This will allow the users to quickly access additional information, regulations, internationals standards, guides and case studies related to the topics they are currently working on.

The common ontology will also allow future applications and modules to access the existing information. Through the ontological structure, such applications may derive inferences of information chains that have not yet been foreseen in current applications. Ultimately, the ontology aims to link the predictive model of AI applications with the input data via conceptual modelling, formality and reasoning capabilities for the topic domain. This may enable explainability and accountability of AI decision aids.

4.3 3D models and point clouds

In order to demonstrate the PLEIADES project, digital models [7] of three different nuclear facilities were used: the Santa María de Garona (SMG) Nuclear Power Plant in Spain; the Halden Research Reactor (HRR) in Norway; and the Base Chaude Opérationelle de Tricastin (BCOT) maintenance facility in France (see Fig. 2). The available data provided by the different owners was analyzed from the perspective of four main areas: costing and planning; radiation to exposure estimation; scenario studies; and waste assessment. The models were completed and enriched with further data so that they could be integrated in the BIM-like methodology.

In the case of some digital models, especially models of facilities that were built several decades ago, the geometrical information may be incomplete or inaccurate (e.g. outdated, not digitized etc.). In order to check whether the geometry is accurate enough or not, point cloud data is either being produced through scan campaigns, or using photogrammetry in the case that the zone cannot be accessed with 3D scans. Thanks to the point cloud data, the actual geometry can be updated so that the simulations are accurate enough (see Fig. 3).

The actual geometrical model is the basis of the physical inventory, as it allows us to make an accurate quantitative analysis. The model continues to be enriched with other data coming from the radiological inventory in an iterative process. Activities performed in this iteration are the analysis of inputs, the identification of gaps or inconsistencies, and the proposal to perform activities to complete the models and be able to perform accurate simulations.

A comparison between different radiological measurements in one given point (hotspots) can also be performed. For that, the fusion of these hotspots with the point cloud data might be relevant.

4.4 Server-based platform development for data and tools integration

In the platform developed in PLEIADES, exchanges of the data generated by the software/hardware tools used in each technology are achieved by using the common data environment (CDE) architecture with an API (Application Programming Interface) exposed for each technology user. The API enables access to the database structured according to the decommissioning ontology [8], and also allows to upload and download different files, mostly IFC (containing data that can be visualized in 3D) and E57 formats (used to store and share point cloud data) (see Fig. 4).

In the PLEIADES project, several issues related to cybersecurity have been identified, such as the requirement for strong user authentication mechanism, data transport layer security or flexible user permission management. These issues, as well as other issues related to the flexibility of data management itself and coverage of other technologies (different from those covered in the PLEIADES project), are planned to be resolved in the DORADO project.

The architecture illustrated in Figure 5 will enable efficient communication between different teams and disciplines involved in the decommissioning planning. The increase of efficiency will be achieved by an automatic data transfer, without need to first manually compile/convert the generated data to separate file formats like e.g. Excel

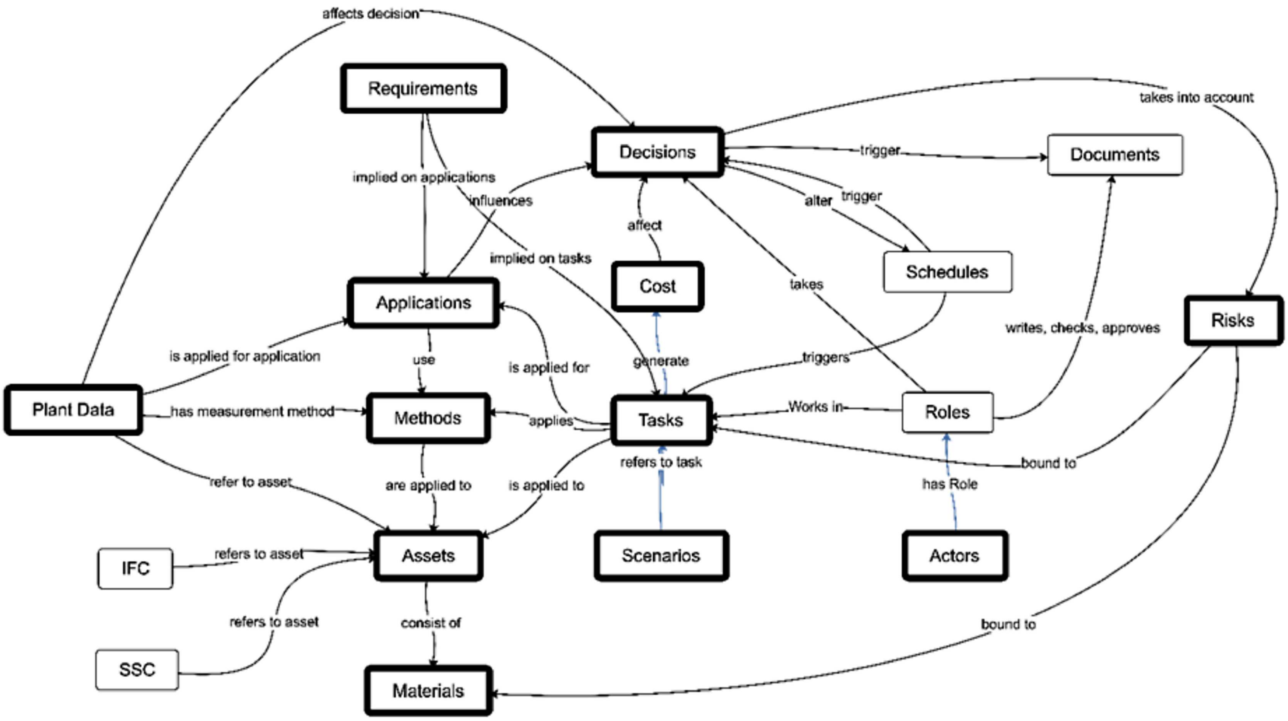

Fig. 1. Core decommissioning ontology [4].

Fig. 2. Implementation of PLEIADES on real use cases.

files, then transferring these data to other team (e.g., via email or FTP access) and finally manually de-compile the data to be used. An additional expected feature of the central application server will be automatic parsing of the uploaded parametric 3D models in "IFC" file format and extracting valuable information into the database, to be accessible by the extended search features of the API.

Already in the PLEIADES project, some techniques were used to implement the cybersecurity, such as OAuth2 authentication protocol and HTTPS secure data transfer layer. In DORADO, these techniques will be further updated. Additionally, new techniques will be implemented, such as stronger user permission management or document management.

The flexibility of data management will be ensured by the adaptation of the data structures and making it compatible to the updated decommissioning ontology.

There is also a plan to extend the API developed in PLEAIDES and make it a more general standard for the centralization and management of digital twin data, potentially reusable in other industry domains. In this regard, a new feature for management of real-time streams is planned to be implemented. Such a feature can be useful

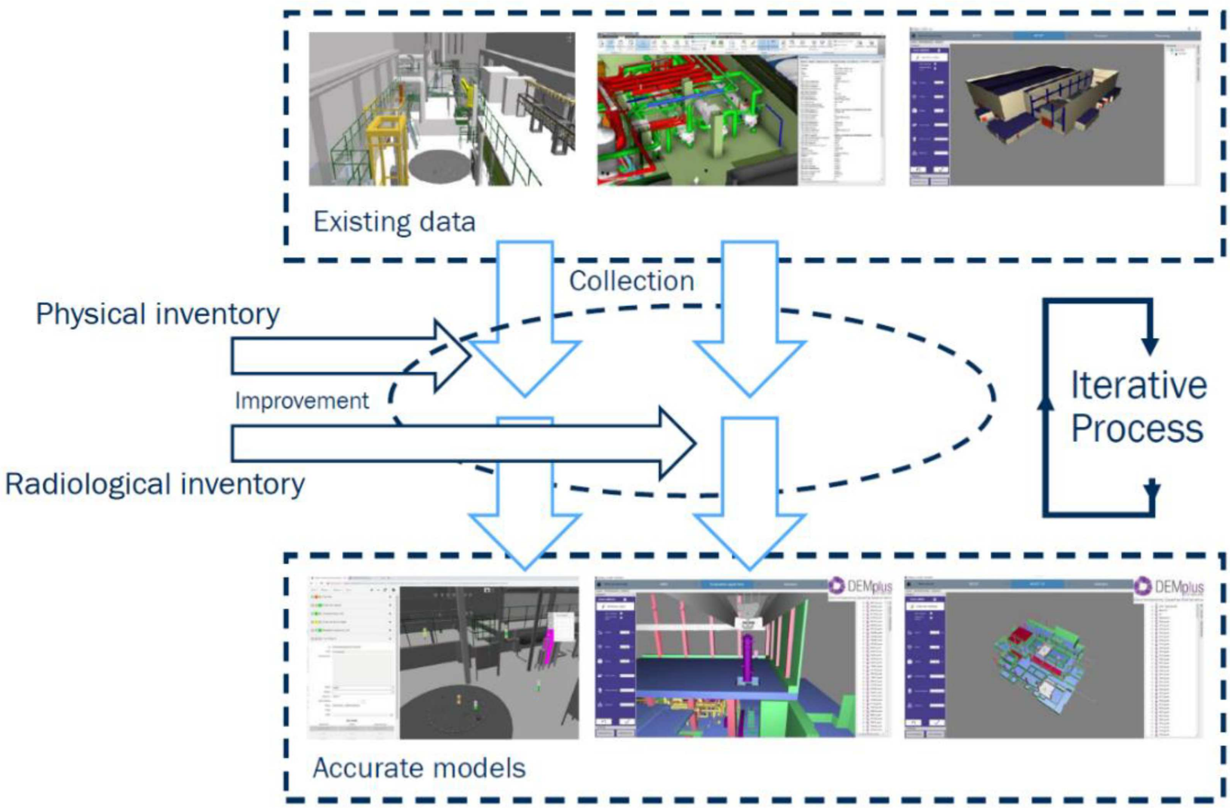

Fig. 3. Use cases 3D models and data in PLEIADES.

for, e.g., storing and retrieving radiological measurements performed by autonomous robots.

4.5 Sensor data fusion with temporal dimension

According to the state-of-the-art technology, sensors such as LiDAR (Light Detection and Ranging), thermal cameras, gamma cameras, dose rate meters, imaging radars, or hyperspectral cameras provide information usually at a single point of time, or in a sequence of time steps, but disconnected from other modalities. These sensors also mostly operate separately without a common frame of reference in temporal and spatial dimensions.

The aim in the DORADO project is to enable automatic sensor data fusion from a large set of sensor modalities that provide disjointed types of information. The solution enables building a more holistic view of the environment, by combining the output of different sensors into a unified frame of reference (see Fig. 6). The solution also enables associating the data samples with a point in the temporal dimension, thus enabling the analysis of changes over time. The unified frame of reference then enables better opportunities for further analysis using the combined information of the different sensor modalities, such as material analysis.

The task of automatically aligning multiple sensor types to a common coordinate system can be quite a complex problem to solve. Therefore, we have limited our practical solution to two specific technical approaches: 1) the sensor is attached to an accurately tracked platform (e.g. a robot or a handheld tablet), or 2) the sensor is attached to a RGB camera that can be accurately positioned in relation to the 3D LiDAR point cloud. We believe that by providing these two approaches we enable a wide variety of use cases with a huge variety of sensor types, while keeping the technical implementation relatively simple and robust.

4.6 Digital twins based ALARA dose estimation

During the PLEIADES project, different use cases considered the workers dose exposure and implemented simulations and scenarios comparisons in order to get the ALARA (As Low As Reasonably Achievable) dose estimation. The HVRC VRdose, RadPIM, DEMplus® and iDROP tools were connected to the PLEIADES platform and used to get dose exposure estimations.

Based on PLEIADES, the DORADO project aims to develop a novel AI/ML (Artificial Intelligence/Machine Learning) model, RADTwin, which will dynamically adapt to changes in radioactive source terms during decommissioning. As dismantling operations alter the geometry and potentially shift the radiation distribution, RADTwin is expected to update the digital twin in real time, enabling more accurate dose assessments while reducing the need for repeated measurements. This approach, if successful, could streamline the radiation protection by adjusting plans based on ongoing structural changes, minimizing the radiation characterization effort

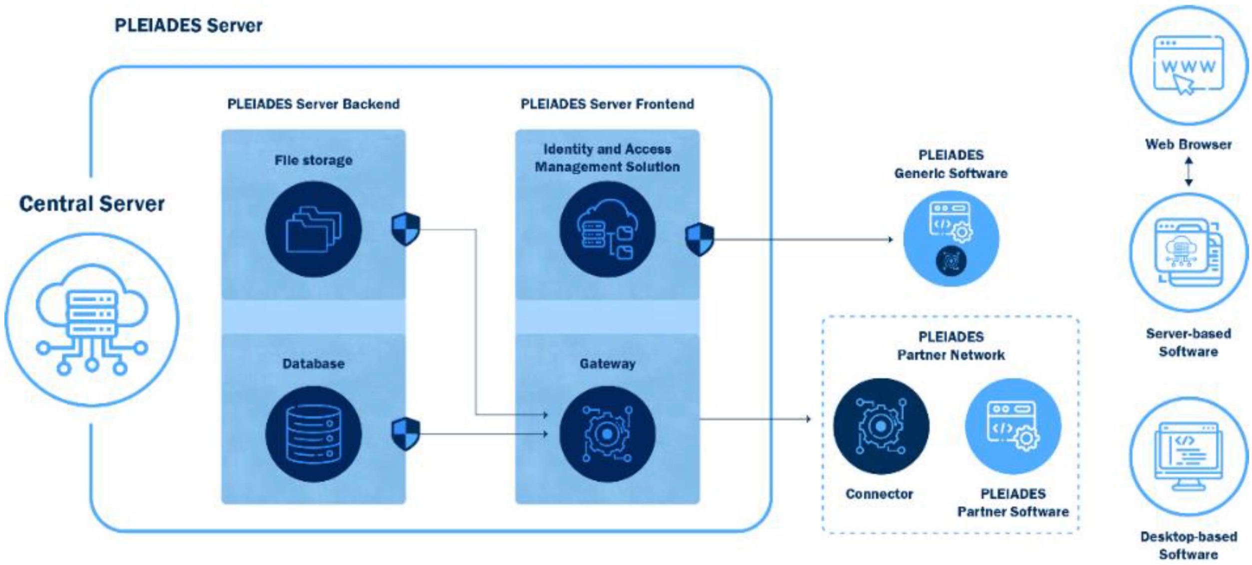

Fig. 4. Server architecture in PLEIADES.

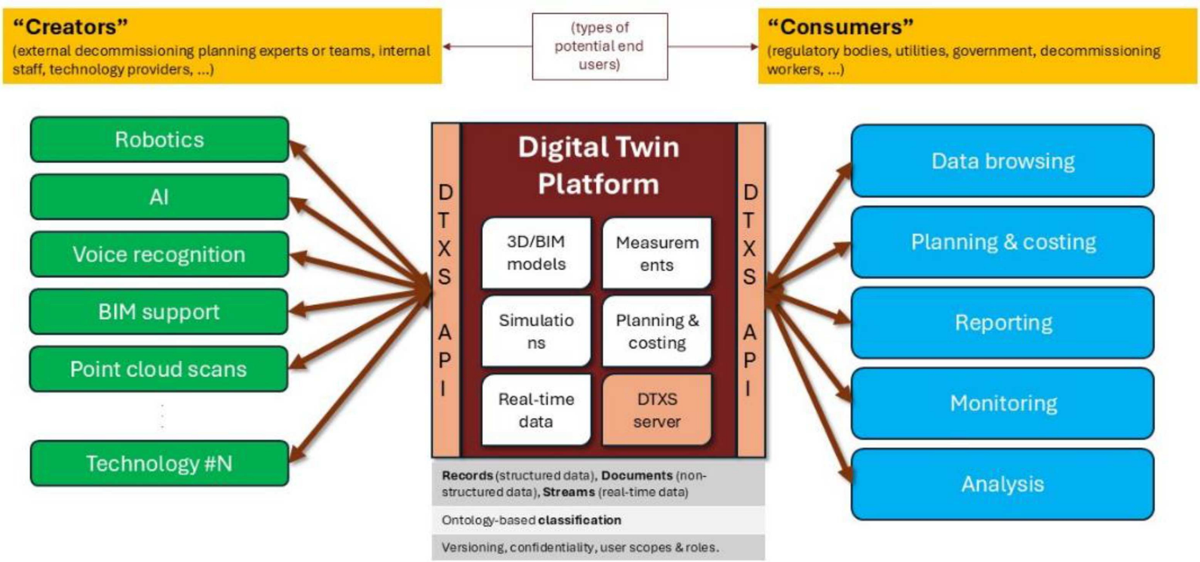

Fig. 5. Illustration of the proposed DORADO architecture.

and the exposure risk while supporting an efficient dose management.

In its intended integration within the RADAR ALARA planning tool, RADTwin aims to address limitations of static models by enabling proactive radiation planning and dose optimization in decommissioning scenarios. By capturing evolving source terms, RADTwin is expected to support more accurate dose management, ultimately contributing to both worker safety and operational efficiency. This research is in its early stages, and the upcoming work in DORADO will focus on evaluating the model's potential to improve the radiological safety through dynamic dose estimation and real-time adaptability within a digital twin framework.

4.7 Mission control, robot route optimization

Through ontological knowledge representation, the system can effectively model and reason about spatial relationships and interdependencies within the environment. This affords the capability to conduct context-aware mission planning and control, facilitating the optimization of robot task allocation. DORADO adopts a more dynamic approach by considering a diverse array of robotic platforms as active agents in the mission planning process. This heterogeneous fleet of robots exhibits a range of capabilities encompassing mobility, sensor functionality, and payload capacity. By treating these robotic agents as active participants, the system can adaptively assign tasks

Fig. 6. The technology initiative, 3D points in green colour represent sensor data, 3D points in blue colour are BIM model, and 3D point cloud in red colour show the missing build elements.

in accordance with their specific proficiency and respond to changes in the decommissioning environment.

The DORADO project integrates real-time worker safety monitoring and risk assessment, leveraging sensory data, semantic mapping, and artificial intelligence in order to discern and mitigate potential hazards related to operating robots. The high-level mission planning in a visual BIM-context will allow adding waypoints and scan points in an easy to communicate way. This can then be sent/imported into the technical detailed mission planning.

4.8 Human-to-System smart voice assistant interface

To complete the data or to update the BIM, 3D or Digital Twin information, a Smart Voice Assistant can be used to capture the observations of field operators. The ambition is to provide a smart voice interface that enables field workers to keep their personal protection equipment on, keep their digital equipment safe (smartphone or tablet protected), and continue to use the digital content during their interventions. During the DORADO project, the following functions will be exhibited:

- show the ability of front-line workers to access digital content by voice based on an agreed ontology. For example, access to information included in the BIM (reference number, location of given element).
- Demonstrate the ability of the front-line worker to report hazardous or unsecure situations related to the SSC (Structures, System and Component), or report discrepancies between the BIM (digital description of a site) and its actual situation (ground truth).

The use of the Voice Assistant technology enables to close the gap between the men and women on the field, and the digital systems like Digital-Twin, BIM or SSC, based on an agreed business ontology.

5 Stakeholder interaction

Nuclear decommissioning is a highly regulated and very conservative domain. Transitioning from operation to decommissioning is a very impactful organizational challenge for many operators. The very different needs for a pragmatic and cost-effective approach to allow a safe decommissioning, not only requires a very different skill set of staff, but also provides major challenges to the IT (Information Technology) infrastructure, data, as well as knowledge management to drive a successful, safe and efficient decommissioning process. Interactions with the stakeholders and the domain actors are a key point to overcome conservatism and promote digital solutions.

During the PLEIADES project, different interactions with stakeholders occurred. At the beginning of the project, a needs and requirements analysis and a gap analysis were performed. A questionnaire-based survey for gathering inputs (habits, expectations, needs, blockers, enablers, etc...) from a large international audience was conducted. The collected results were then presented and ordered during a dedicated session at DigiDecom2021 workshop. During the implementation, the project's accomplishments and achievements have been shared with a broader scientific and industrial audience through papers and presentations at prominent international nuclear conferences and their proceedings (see for example [9], [10]). After the identification of potential synergies between the project activities and the agencies' programs, the project members also participated in agencies' activities, especially concerning the knowledge management and the standardization process. Yearly newsletters have also been widely broadcast to the stakeholders. Finally, an open workshop was held during the DigiDECOM2023 conference for promoting the consortium and the project outcomes. During this workshop, the PLEIADES consortium received feedback that encouraged the path to, among others, DORADO.

Regular interactions with the stakeholders will continue during the DORADO project. An end-user network is formed at the beginning of the project to ensure that the planning is practically implementable and meets the actual needs. The impact of the potential new technologies on the business will be examined through interviews and work meetings, aiming to identify the key cause-and-effect chains affecting competitiveness. Co-operation continues throughout the project starting from identifying the needs and requirements to eventually demonstrating and deploying the technologies to be developed.

The combination of end-user integration into the project, demonstration applications, case studies, training and other dissemination actions (e.g. presentation on conferences, integration into the decommissioning projects of the participants) will show further potential of the holistic digitalization approach for the decommissioning. In addition, the project is aligned with other approaches of international organizations to make their knowledge bases more accessible using ontologies. This is not only important for increasing the public acceptance of nuclear energy as low-carbon energy production, but also for invoking dissemination measures concerning the digitalization of decommissioning.

6 Conclusion

Digital tools are under a very fast development in many fields of industry. Moreover, the nuclear safety is highly regulated and safety critical field can provide a challenging demonstration environment for emerging new technologies. In the PLEIADES and DORADO projects, both digital tools and nuclear safety can learn from each other reciprocally.

The main expected impacts are minimizing the radiation exposure and the risk of occupational incidents to workers, as well as increasing the efficiency of decommissioning planning by enabling remote operations and planning. This can result in significant cost reduction and optimized Waste Management (WM) strategies among others, increasing the social acceptance towards the nuclear energy.

PLEIADES provided a first pilot integration of front-line digital decommissioning and waste management support tools, by creating the central server for combining different data and ensuring the compatibility and using an ontology that is compatible with the existing standard information representations and is sufficiently comprehensive to represent the processes in the nuclear back end. It demonstrated the usefulness and efficiency of this concept using 6 scenarios based on 3 real nuclear sites.

The DORADO project will continue this work by creating a holistic digital platform based on a data-driven approach and integrating digital tools into a coherent suite customized for decommissioning applications. The eight technologies implemented in the project will be integrated with a common data server combining the data flow following the BIM methodology. These technologies include: point-cloud data, 3D models and change detection, Digital Twins (DTs) based ALARA dose estimation, robot mission optimization, and smart voice assistant interface. After the technological development phase, the results will be demonstrated with data sets collected from real nuclear facilities. Data collected for the PLEIADES project will be partially reused, but new test cases are also considered as for example the FiR1 research reactor site in Finland.

The platform could also be fed with results of other collaborative projects, for example robots capabilities data coming from the XS-ABILITY project [11] results.

Once completed, such a platform can be effectively utilized for preparing and monitoring decommissioning activities, especially for: in situ waste characterization, planning waste segregation and packing remotely, robotics and remote handling systems, clearance of surfaces and structures, cost estimation, risk identification and knowledge management. Benchmarking digital tools with demonstrations from nuclear facilities also can assist the regulators to understand the future technical possibilities and to update the regulations to cover all the changes in the operating environment.

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Conflicts of interest

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Data availability statement

Data associated with that article cannot be disclosed due to nuclear & industrial confidentiality reasons.

Author contribution statement

Marie-Bénédicte Jacques: PLEIADES project administration; Writing: 1, 2, 4.1, 4.2, 4.6, 5; Review and editing: all. **Antti Räty**: DORADO project administration; Writing: 3, 4.5, 4.6, 4.7, 4.8, 5, 6; Review: all. **Joseph A. Ridao Cabrerizo**: Writing: 1, 3, 4.1, 4.2, 4.3; Review: all. **Dusan Daniska**: Writing: 2, 4.2, 4.4; Review and editing: all.

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