Digital twins and Ontology for Robot Assisted Decommissioning Operations

DORADO

Innovation Action (IA)

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State-of-the-Art and Business Value Analysis Report

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Summary

This deliverable provides a comprehensive analysis of an integrated technology platform for nuclear decommissioning, particularly for complex legacy sites. It begins with a State-of-the-Art review, examining current practices and existing technological advancements in the field. Following this, a detailed Business Value Analysis is presented, demonstrating the significant advantages of adopting this platform.

The report highlights how the integration of inspection robotics, point cloud technology, Building Information Modeling (BIM), ontology, digital twin, and voice assistance can improve the decommissioning process. It analyzes the value for specific use cases by enhancing safety, improving efficiency, optimizing costs, strengthening data and knowledge management, and promoting sustainability. The analysis advocates for a realistic, graded implementation approach, acknowledging the nuclear industry's conservative nature, to ensure successful adoption and maximize the platform's transformative potential.

Approval

Date	**Approved by**
2025-06-24	Jose Ridao and Tapani Ryynänen

Executive summary

This deliverable presents a comprehensive analysis of the current landscape of multiple technologies that can support the nuclear decommissioning, and the compelling business case for adopting an advanced, integrated technology platform. The decommissioning of nuclear facilities, particularly legacy sites, poses significant challenges due to incomplete historical data, unknown hazards, and the inherent risks of human intervention in radioactive environments. This report first reviews the existing state of technological advancements relevant to these challenges, identifying both current capabilities and areas for innovation.

The core of the proposed solution is an integrated digital platform that combines several cutting-edge technologies. This includes advanced robotic systems capable of navigating hazardous and difficult-to-reach areas, equipped with sophisticated sensors for detailed site characterization. Three-dimensional spatial mapping, using precise digital representations of physical environments, forms the foundation for comprehensive digital models of the facility. These models are intelligently structured by an ontology and a central knowledge framework, enabling efficient data handling and analysis. A dynamic virtual replica of the facility allows for realistic simulations and real-time monitoring, while a voice-assistance facilitates the reporting process with enhanced operational efficiency and safety for personnel. The platform also incorporates advanced simulation tools to model radiation fields and validate operational plans in a safe, virtual setting before real-world deployment.

The business value of this integrated platform is substantial, demonstrating significant advantages across critical areas of nuclear decommissioning. It dramatically enhances safety by minimizing human exposure to radiation and hazardous conditions through remote operations and proactive hazard identification. Efficiency is greatly improved by accelerating site assessments, automating routine tasks, and optimizing planning processes. The platform contributes to cost reduction through reduced labor needs, minimized rework, and more effective waste management strategies. Furthermore, it strengthens data and knowledge management by ensuring the completeness, accuracy, and accessibility of critical information, enables better decision-making and collaboration. Finally, the platform promotes sustainability by enabling optimized resource utilization and reducing environmental impact, such as minimizing waste generation.

Recognizing the nuclear industry's cautious approach to new technologies, this report advocates for a realistic, graded implementation strategy. This phased adoption allows for systematic demonstration of value in specific use cases, building confidence and facilitating a smoother transition. By focusing on the synergistic capabilities of these integrated technologies, the platform aims to enhance legacy site management, ensuring safer, more efficient, cost-effective, and environmentally responsible decommissioning outcomes.

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Abbreviations and acronyms

Acronym	Description
AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
ALARA	As Low As Reasonably Achievable
APF	Artificial Potential Field
API	Application Programming Interface
ASR	Automatic Speech Recognition
BIM	Building Information Modelling
BIMfD	BIM for Deconstruction
CAD	Computer-Aided Design
CDE	Common Data Environment
CLEANDEM	Cyber physicaL Equipment for unmAnned Nuclear DEcommissioning Measurements
CONCERT	CONfigurable CollaborativE Robot Technologies
DORADO	Digital twins and Ontology for Robot Assisted Decommissioning Operations
DT	Digital Twin
DTXS	Digital Twing eXchange Standard
D&D	Decommissioning and Dismantling
EU	European Union
EC	European Commission
EU	European Union
EURATOM	European Atomic Energy Community
HARPERS	HARmonised PracticEs, Regulations and Standards in waste management and decommissioning
HTTPS	Hypertext Transfer Protocol Secure
IFC	Industry Foundation Classes
JSON	JavaScript Object Notation
JWT	JSON Web Token
KBI	Key Business Indicator
KPI	Key Performance Indicator
LiDAR	Light Detection And Ranging
LLM	Large Language Model
LQR	Linear Quadratic Regulators
MASLAM	Multi-Agent Simultaneous Localization And Mapping
MC	Monte Carlo
ML	Machine Learning
MLLM	Multimodal Large Language Model
OWL	Web Ontology Language

PC	Point Cloud
PLEIADES	PLatform based on Emerging and Interoperable Applications for enhanced Decommissioning processES
RDF	Resource Description Framework
ROI	Return on Investment
RPO	Radiation Protection Officer
SAR	Safety Analysis Report
S-KPI	System-level Key Performance Indicator
SIM	Safety Information Model
SKOS	Simple Knowledge Organization System
SLAM	Simultaneous Localization And Mapping
SotA	State-of-the-Art
THMC	thermal-hydrological-mechanical-chemical
T-KPI	Technology-specific Key Performance Indicator
TLS	Transport Layer Security
TTS	Text-to-Speech
UGV	Unmanned Ground Vehicle
URI	Universal Resource Identifier
VPN	Virtual Private Network
VPR	Visual Place Recognition
VUI	Voice User Interface
XS-ABILITY	Accessing hard-to-reach areas with Advanced and Breakthrough Innovation for reLiable In-situ characterization of a faciliTY

Figures and Tables

Figures

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1 Introduction

1.1 Overview of DORADO

The safe and efficient decommissioning of nuclear facilities is a critical challenge for the global energy sector. Aging infrastructure, hazardous environments, and strict regulatory requirements demand innovative solutions to reduce risks to workers, the public, and the environment. Advances in robotics and digital technologies, such as Digital Twins (DTs, virtual models of physical systems) and ontologies (structured frameworks for organizing knowledge), offer promising tools to address these challenges.

The DORADO (Digital twins and Ontology for Robot Assisted Decommissioning Operations) project aims to enhance the safety and effectiveness of decommissioning tasks by integrating these technologies. By creating accurate digital replicas of nuclear facilities and establishing standardized ontologies, the project seeks to improve communication between robots, operators, and systems, enabling better planning, real-time decision-making, and collaboration. To realize these goals, a set of technological modules are integrated to form a cohesive system. This includes artificial intelligence (AI) for adaptive decision-making, building information modeling (BIM) for 3D facility mapping, sensor fusion to harmonize real-time data streams, and voice assistance to facilitate systematic and easy reporting for site inspections. At the core of this system lies an ontology-enabled central server, which standardizes and streamlines data exchange between modules, ensuring seamless collaboration and enhancing the safety, precision, and efficiency of decommissioning workflows.

1.2 Purpose of the Document

This report is composed of two parts. The first part (chapters 2 and 3) provides a state-of-the-art review and literature survey to map existing research, technologies, and gaps in the fields of digital twins, ontologies, and robotic systems for nuclear decommissioning. By analyzing current approaches, we aim to identify opportunities for innovation and lay the groundwork for DORADO's technical development. The findings will support the creation of a robust, adaptable framework to address the complex demands of decommissioning operations.

The second part (chapters 4-6) discusses the business vale analysis of the proposed platform. The analysis involves the definition of key use cases for the platform, followed by definition of the key performance and business indicators to provide some basis for the assessment. This is then followed by highlights needed for a realistic analysis, needed to quantify the costs versus the benefits gained.

The last two chapters (excluding the bibliography chapter) conclude the report by suggesting a high-level implementation plan before introducing the conclusions and recommendations.

2 Background

2.1 DORADO Platform Overview

The DORADO platform is designed as an integrated, intelligent system to address the complexities of nuclear decommissioning by unifying advanced digital tools into a collaborative framework. At its foundation, the platform combines Digital Twins — as dynamic virtual replicas of physical facilities— with a structured ontology to standardize knowledge representation and ensure consistent communication across all components. Central to the platform is a Building Information Modeling (BIM) module, which provides a detailed 3D digital representation of the facility, enabling precise spatial planning, asset tracking, and real-time updates during operations.

Key functionalities of the platform include AI-powered adaptive task planning, 3D spatial awareness via fusing data collected by robots through sensors and modalities, and seamless interaction supported by voice assistance and speech recognition. A central ontology-enabled server acts as the backbone, harmonizing data exchange between modules and maintaining interoperability across hardware, software, and human operators. Illustration of the data flow and data management architecture is shown in Figure 1.

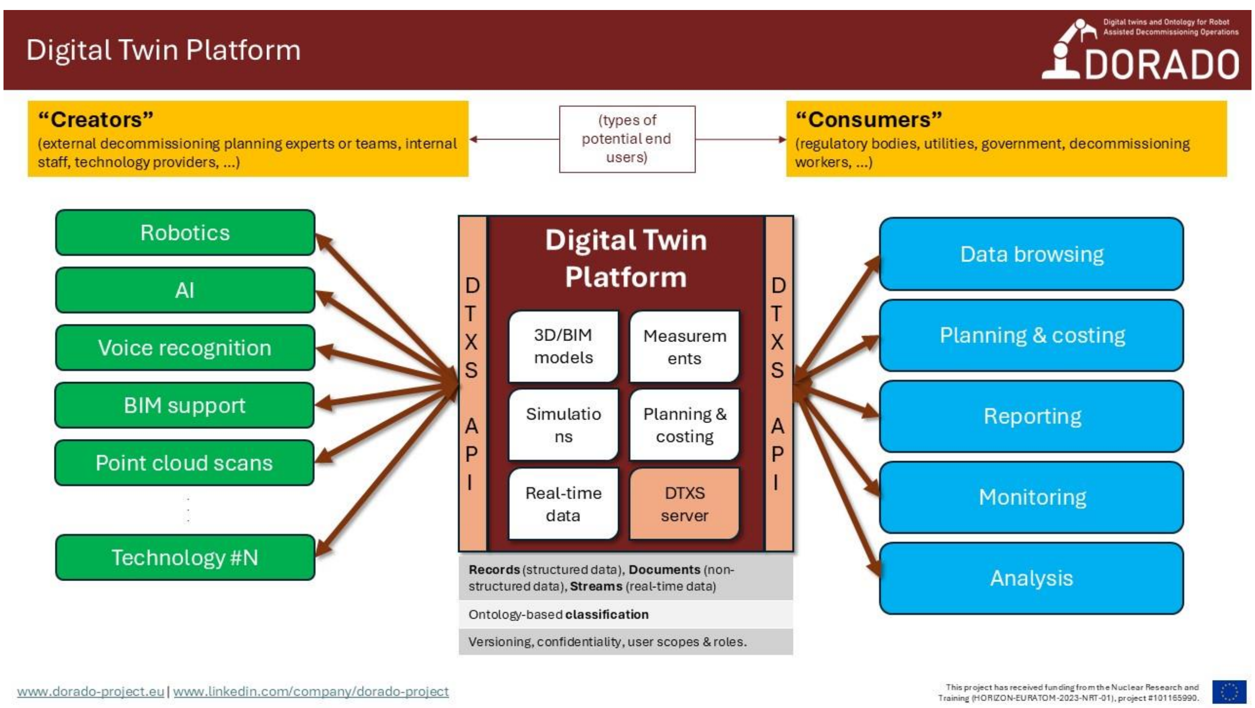

Figure 1: Illustration of data flow and data management architecture of DORADO platform.

2.2 Technologies Integrated in the DORADO Platform

Description of the 8 technologies integrated in the platform

2.2.1 Sensor data fusion with temporal dimension

DORADO aims for a robust automatic solution for performing data fusion from different sensor modalities enabling operational environment data collection. Data fusion is developed also to support temporal dimension, i.e. data points can be associated across temporal dimension, thus supporting data processing as a time series.

A focused set of software solutions is used for automatic data registration into a one unified coordinates system. For this purpose, two main interest areas were identified: 1) sensors on tracked platforms (e.g. robots), and 2) sensors in a calibrated rig with a camera. Usually, the first approach is adequate for generic use cases. The latter approach provides support for automatically aligning handheld sensor data or e.g. drones which do not always have so accurate tracking. The latter approach is useful also with the kidnapped robot problem, which is not normally a real issue. However, in the case of a robot that could easily recover localization from an arbitrary location it would provide some addition flexibility to the robot's use.

Below, the background technologies related to these two approaches are described in more detail.

Sensors on tracked platforms

Robots and other tracked platforms provide relative metric location in real-time. This can be done with Simultaneous Localization And Mapping (SLAM), or alternatively the robot can navigate using premade maps of the environment. A common approach to acquiring a global position based on this locally tracked position is to start the robot from an accurately known global position. If the robot is properly tracked and the sensor is attached to the robot, this enables automatic data registration to a common coordinate system.

Sensors in a calibrated rig with camera

A visual localization solution can automatically be aligned to a photograph with a reference 3D LiDAR scan. This is implemented as a network service with a RESTful API interface. This approach is novel, but it utilizes many state-of-the-art methods that are described in more detail in chapter 3.2.1.

The above localization solution can be used to align sensor information with a global coordinate frame, when we use a fixed rig where the relation between the camera and the sensor is calibrated/known.

2.2.2 Environment data comparison against BIM

A key topic within the DORADO project involves maintaining accurate representation of the dynamic environment in a facility undergoing decommissioning. Daily modifications can vary from minor adjustments, such as sections of piping being removed, to major structural changes, like the removal of entire walls or significant equipment relocation. Precisely identifying and documenting these changes is crucial to support effective mission planning, especially for autonomous robotic systems.

The literature review reveals a growing body of research dedicated to the comparison of point clouds with environmental and BIM data, particularly focusing on methods for deviation analysis and model integration. Notable contributions in this area include the work of [1], who introduced a deviation analysis approach that systematically compares BIM models with actual conditions captured from point clouds, thereby enabling the identification of discrepancies between design intent and as-built reality. Similarly, [2] presented one of the earliest automated methods for BIM-point cloud comparison, focusing on the assessment of dimensional deviations to support quality control and progress monitoring. Building on these foundations, [3] proposed a specialized methodology for comparing point clouds with BIM geometry, particularly for structural components, offering practical insights into the application of such techniques in real-world construction scenarios.

Another significant area of research concerns the integration of IFC and point cloud data, which is essential for the automated generation of as-built BIM models. [4] provided a comprehensive review of various techniques for automatically generating IFC-format BIM models from point clouds, highlighting both the strengths and limitations of current approaches. [5] further advanced this field by detailing algorithms that map laser scan data to IFC elements, a process that is critical for achieving interoperability and semantic richness in BIM environments.

An effective method to maintain an accurate digital representation of the facilities status involves systematically comparing collected point cloud data with existing Building Information Modeling (BIM) data. By performing regular, detailed comparisons, one can reliably identify differences that emerge due to physical changes in the facility.

When comparing point clouds with BIM models, a structured approach will be implemented. Initially, preprocessing the point cloud data, such as filtering and noise removal, ensures accuracy and reduces false positives. Following preprocessing, registration and alignment methods accurately overlay the point cloud with the BIM model, allowing for direct comparison. Computational techniques, including change detection algorithms, can then be applied to automatically detect, classify, and quantify discrepancies between the two datasets as explained below in subsection 3.2.3.

Identified changes can be classified based on their nature, magnitude, and potential impact on ongoing operations. This classification step facilitates prioritization of updates to the BIM model, determining whether immediate revision is required or if updates can be scheduled alongside periodic reviews.

Finally, the insights derived from detected differences can be systematically integrated back into the BIM environment. This integration involves not merely acknowledging the presence of changes but explicitly recording their nature and extent, ensuring that the BIM model remains a reliable and authoritative source of truth for the current state of the facility.

2.2.3 Point cloud and 3D model change detection

Change detection is especially useful for comparing the changes that occurred in the same environment during two or more different periods of time. A comparison between point clouds, between digital 3D models, or between point clouds and 3D models may be possible and useful (e.g. identification of the geometrical deviations, creation of heatmaps according to a certain tolerance

previously established, etc.). In the use case of DORADO, the application of change detection may address real environments where decommissioning will be carried out over a certain period. Change detection between different epochs is very helpful, as a lot of elements may change during the decommissioning process. These elements can be totally or partially removed at each step.
Existing autonomous robotic platforms allow 3D point cloud scans and photographic imaging. The acquisition of geometry in a real environment through the creation of point clouds is a necessary step either prior to creating a digital model, or to verify and update the geometry (3D). These tasks are especially necessary in the case of facilities that were built several years ago, and for which there is not enough updated information. Accurate geometrical information is the basis for the creation of a digital model. This model can be enriched with further information (e.g. radiological information coming from gamma scanning). The coupling of geometry and radiological information is a functionality being currently extended.

In DORADO, semi-automatic change detection is to be implemented for comparing subsequent point-cloud scans and/or 3D models corresponding to two or more different periods of time in the same environment. The project aims to use AI to increase the efficiency of performing detection of changes (partially) autonomously. This may allow the identification of geometrical deviations or the creation of heatmaps according to a certain tolerance established, among other functions.

2.2.4 Digital twins based ALARA dose estimation

The ALARA principle (As Low As Reasonably Achievable) is part of radiation protection programs worldwide, usually mandated and audited by regulatory frameworks. Its primary goal is not only to optimize radiation exposure to personnel but also to reduce operational costs and minimize radioactive waste generation. Recently, state-of-the-art radiation protection strategies have been evolving toward improving operational efficiency, reducing radioactive waste, and lowering worker radiation exposure, especially in Decommissioning and Dismantling (D&D) activities.

Radiation Protection Officers (RPOs) and ALARA analysts typically rely on manual or semi-automated approaches to estimate radiation doses. This involves constructing geometric models and defining radioactive source terms using data from radiological characterization surveys, hotspot identification, or routine radiological measurements. Due to practical limitations such as time constraints, complexity of facility geometries, and incomplete radiological data, analysts frequently must make significant approximations, impacting the accuracy of the dose assessments, which might lead to overestimation or underestimation of the operation cost and the dose reduction measures.

Dose estimation generally follows two complementary methodologies:

1. **Direct Radiological Measurements:** This approach includes characterization surveys, dose-rate mapping, gamma spectroscopy, and hotspot identification. These measurements provide reliable empirical data but usually represent limited coverage and may not fully capture the dynamic evolution of radiation fields, especially during Decommissioning and Dismantling (D&D), where conditions continuously change due to the removal of activated materials.

2. **Computational Modeling:** When sufficient geometric and radiological data are available, computational modeling provides more comprehensive dose assessments. Currently, two primary computational methods dominate:

- Point-Kernel Methods:

  Simple tools, like MicroShield, offer practical usability and rapid results. However, these tools typically restrict users to predefined, simplified configurations, requiring assumptions and reducing accuracy.
- Monte Carlo (MC) Simulations:

  MC simulations (such as MCNP and Geant4) accurately simulate complex geometries and radioactive source distributions. Despite their accuracy, they demand specific expertise and considerable effort for preparing input files, limiting their routine application in operational environments due to complexity and lack of user-friendly interfaces.

Over the last decade, more user-friendly computational dose estimation tools have emerged, attempting to balance accuracy with practicality. However, most still lack automated integration of Digital Twin (DT) environments and real-time sensor data to update the changes in the environment.

DORADO is specifically focused on addressing these limitations in the context of D&D operations, where both geometry and radiation fields continually evolve. The tool RADAR, which incorporates both point-kernel and Monte Carlo calculation capabilities with a user-friendly interface, will be used. Currently, RADAR supports importing detailed CAD geometries and radiological survey data such as dose-rate 3D maps.

One of the key objectives of DORADO is to automate the integration of Digital Twins created by other project technologies into RADAR. Robotics equipped with radiation sensors and advanced geometry scanning systems (e.g., LiDAR, photogrammetry, and RGB-D cameras) will continuously capture changes occurring during dismantling operations. Sensor fusion technologies will ensure identification of geometric and radiological changes, automatically updating the Digital Twin environment adopted by RADAR.

Additionally, an adaptive module within RADAR will be developed to dynamically update radiological source terms and geometry models based on these sensor inputs and robotic surveys, reducing manual intervention. The implementation of a standardized ontology within DORADO will define uniform data formats across different sensor types and manufacturers, improving compatibility and interoperability across integrated technologies.

By integrating robotics-based radiological surveys, advanced geometry scanning, sensor fusion technologies, and ontology-driven data interoperability into RADAR, the DORADO platform aims to enhance the accuracy, efficiency, and compliance of ALARA dose estimation in evolving nuclear environments characteristic of D&D projects.

2.2.5 Server-based integration with IFC file format and extended data queries

Server-based integration

Integration of various technologies and especially integration of data used by these technologies into a single data management platform requires an IT architecture fulfilling at least the following requirements: open, flexible and modular. First, openness can be achieved by two main approaches: by using other open technologies (3rd party software libraries), protocols and formats as much as possible and by providing well-structured and comprehensive documentation. Second, flexibility should be considered from the perspective of being able to update data structures maintained by the platform and being able to communicate with any technology connected to it. And thirdly, modularity is a key feature to being able to achieve both flexibility and interoperability.

To satisfy these requirements, the RESTful-based API has been selected as a data transfer protocol, the JSON format as a data storage for storing structured data and IFC file format for storing 3D models.

Additionally, hence the platform is developed in the environment handling with very sensitive data (nuclear decommissioning), the data security must be kept at the highest level possible. To achieve this, mature security protocols and libraries should be used. Based on our analysis and based on the experience from previous similar projects, the OAuth 2.0 authentication and authorization protocol has been selected to be used.

Extended data queries

Centralized data management provides a strong backbone for integration of different digitalization technologies used in the DORADO project (and in nuclear decommissioning). To make this data management flexible enough and easily utilizable by any technology, it should provide an interface (protocol) which enables fetching data from different perspectives, e.g.:

- Each technology works with different data sets or data structures
- Each project / decommissioning scenario / demonstration needs different views on existing data sets, e.g. different statistics or summary reports

This interface will be implemented and fully described in order for all DORADO project partners to be able to learn how to query and fetch as many data structures or data sets as possible. For example, a data fetch query to get information described as, for example, "*list all buildings where a person XYZ has planned to perform a job*" will be provided by the interface. It is not planned to make the interface understand humanly expressed queries (no natural language processing is expected), but the syntax and flexibility of the fetch queries should be as high as possible. To improve understandability of the search queries and data structures that can be queried/fetched by the protocol, the nuclear decommissioning ontology developed alongside during this project will be utilized to describe (classify) the data managed by the platform.

The interface is already in development, and it's called **Digital Twin data eXchange Standard (DTXS)**. During the project, the capabilities of the interface will be further extended.

2.2.6 Mission control and robot route optimization

The mission control component of DORADO acts as the central system for overseeing and directing robotic operations during decommissioning tasks. It combines real-time data from sensors, facility maps, and robotic systems to monitor progress, identify risks, and adjust plans as conditions change.

Robot route optimization focuses on planning and adjusting the safest and most efficient paths for robots to navigate complex nuclear facilities. The system accounts for factors such as structural obstacles, radiation levels, and task priorities, using automated analysis to balance speed, safety, and resource use. By integrating up-to-date facility data from BIM models and sensor inputs, the platform dynamically updates routes to adapt to unexpected challenges, ensuring smooth operations even in unpredictable settings.

The process begins with **mission planning**, where the user defines the overarching goals of the operation (e.g., "scan Room A"). The planning relies heavily on the DORADO ontology, a structured knowledge framework that encodes relationships between facility components (e.g., pipes, valves, drums) and safety protocols. Ontology helps prioritize tasks, allocate resources, and identify dependencies to ensure compliance with safety standards.

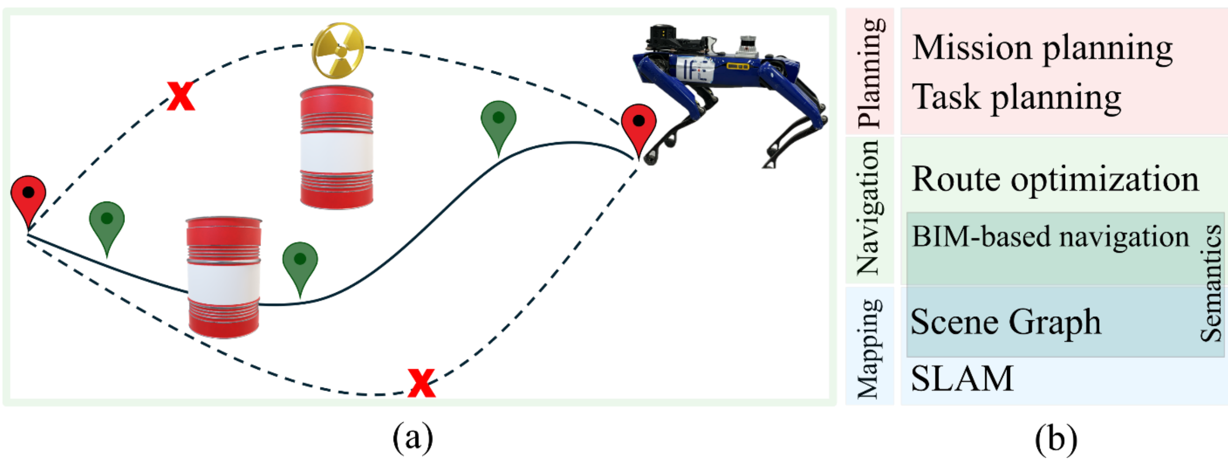

Figure 2: (a) The robot route optimization going from scan points (red marks) while minimizing radiation exposure. (b) The robotic-related tasks and categories.

Mission goals are then decomposed into actionable steps through **task planning**. For example, "scan Room A" might translate to sequences like "scan surfaces for radiation" and "check for leakage". Task planners use rules from the ontology (e.g., sensor compatibility, hazard zones) and real-time data to generate executable workflows.

With tasks defined, robots execute **navigation** using BIM/IFC maps (precise 3D facility models) as a spatial reference. **Route optimization** is carried out dynamically to avoid obstacles, minimize radiation exposure, and reduce travel time. The system balances pre-planned paths (from BIM data) with real-time updates, integrating inputs from LiDAR, RGB-D cameras and other sensors to refine positioning. The robots run a **SLAM** algorithm to generate maps for the environment keeping in consideration possible drastic changes compared to the previously built or generated maps. SLAM can run across multiple robots jointly to contribute to the mapping process, which is known as multi-agent SLAM (**MASLAM**). This collaborative approach allows robots to share information, which can lead to faster and more efficient mapping compared to single-robot SLAM.

To achieve richer digital representations, **semantic mapping** enables robots as well as digital tools to interpret, organize, and relate complex data through shared semantics, enhancing interoperability and data understanding. Semantic mapping involves visually or structurally representing the relationships and meanings between data points, concepts, or objects, allowing systems to connect, categorize, and contextualize information for improved analysis, collaboration, and decision-making. One form of representation is **scene graph** which is a representation of objects and their spatial relationships. These can be constructed, combining BIM data with live sensor inputs to model the environment.

2.2.7 Human to System smart voice assistant interface

The Smart Voice Assistant SPIX will be used in DORADO to close the gap between the field operators and their digital systems: digital twins, BIM, risks and hazard estimation tools. SPIX enables field operators to report observed differences between the ground thought and the Digital Twin/BIM data while on the field, hence improving the accuracy of the digital content used for mission planning, and the safety of future interventions.

Figure 3: The field operator makes use of voice to keep his hands free while reporting issues, remarks, measurements, etc. When back to a connected area, the generated data are transferred to the related system.

The goal of voice interactions is to free the hands of the operators at work, reduce the time of their presence in hazardous situations (according to ALARA), prevent the contamination risk of documentation devices, and enhance the quality of the data reported onsite.

In DORADO, voice assistance will make use of a “business specific” ontology creating a dynamic knowledge representation system that adapts to evolving data and user needs, enhancing the platform's decision-making capabilities and knowledge management. The voice assistant technology will be interfaced to the BIM information: get information on the field, report discrepancies from the field in real time by voice, report new hazardous situation by voice from the field in real time.

The current need of voice in the nuclear industry can be summarized as follows:

- Help field operators to interact with business data: get workorder, access documentation, generate field reports and Retex;
- Promote a safe use of digital equipment, keeping gloves and helmets, focusing on the environment;
- Work 100% offline in disconnected situations.

The expected improvements enabled by the DORADO project considering the use of voice and voice assistance by field operators are:

- Enhance the safety of field operators with real-time information on the status of the construction/deconstruction;
- Increase the level of data of critical installations by considering the field operators' feedback and process it automatically;
- Tackle the obsolescence of the BIM and Digital Twins by considering the updates from the field operators.

2.2.8 Standardization using the common ontology

Ontologies are formal, schematic representations of a knowledge domain and form a model of the reality [6], [7]. They consist of a vocabulary and rules for its composition and are used as content-describing metadata in various (internet-) services and are establishing themselves as an additional method of knowledge organization, which is increasingly being used alongside classical methods (such as Thesauri). Ontologies are written in machine-readable ontology languages so that computer systems can automatically read and, if possible, interpret the information (Weller, 2013).

The components of an ontology are composed of (Weller, 2013):

- concepts, mostly hierarchically ordered and implemented and defined in the form of classes;
- instances as concrete elements of these classes;
- properties as descriptions of the characteristics of and relationships between concepts;

restrictions can model the structure of an ontology.

The ontology in DORADO serves as a model to achieve a common understanding of the field of interest and its major concepts. Based on the ontology, the structure of the software components will be developed.

2.3 Role of AI in DORADO

Artificial intelligence is expected to play a crucial role in the development of the DORADO project.

In April 2021, the European Commission proposed the first EU Artificial Intelligence Law, establishing a risk-based AI classification system according to the risk that AI systems pose to users. In June 2024, European Union lawmakers signed the artificial intelligence, the AI act. Some AI systems presenting 'unacceptable' risks are prohibited. A wide range of 'high-risk' AI systems that can have a detrimental impact on people's health, safety or on their fundamental rights are authorized, but subject to a set of requirements and obligations to gain access to the EU market. AI systems posing limited risks because of their lack of transparency will be subject to information and transparency requirements, while AI systems presenting only minimal risk for people will not be subject to further obligations. The AI Act was published in the EU's Official Journal on 12 July 2024. It entered into force in August 2024. This framework will be considered when developing the use of AI in the DORADO project.

The DORADO Specific Technical Objective 1 is to demonstrate the utilization of AI-based technologies in decommissioning planning. Detecting changes in point-clouds, optimizing robot mission planning based on measurement results and providing guidance automatically through smart voice assistance technology are potential areas for AI applications. AI enables automatic planning procedures to minimize or avoid all unnecessary physical exposures (e.g. risks related to radiation / radioactivity). Digital twin models supplement AI with data for automated processes. Applications include e.g. human-robot interaction, facilitate planning future planning operations and augments human-robot interaction. Digital twins and AI will be used, e.g. in optimizing robot mission control inside a nuclear facility.

The DORADO Specific Technical Objective 2 is to enhance the coverage of the existing decommissioning ontology. Within the highly regulated D&D domain, underlying principles of decision making are crucial. The objective of providing an ontology is to link the predictive model of the AI with the input data via conceptual modelling, formality and reasoning capabilities for the topic domain.

The “Artificial Intelligence” is a very broad term, covering a lot of technologies with one common aspect – it needs a large amount of data with some level of quality for the AI models to be trained. In most cases, the “AI” covers two different approaches, namely machine learning (ML) and large language models (LLM). Machine learning is a subset of AI where technologies can learn from provided data (mostly structured data) without explicit programming and may be helpful in, e.g. optimization, automation or monitoring tasks. On the other hand, large language models are primarily used for understanding human language and may be helpful in data extraction or document search tasks.

Recently, multimodality has been an active topic in artificial intelligence research. The multimodal large language models (MLLM) combine the reasoning capabilities of LLMs with ability to understand and output multimodal information. This allows us to use audio, image, and video information together with text-based understanding. MLLMs bring new technological opportunities e.g. for computer vision, audio processing and spatial understanding.

Regarding point-cloud and 3D model change detection, AI will be used to increase the efficiency to perform detection of changes (partially) autonomously. This will allow the identification of geometrical deviations or the creation of heatmaps according to a certain tolerance established, among other functions.

Regarding Digital twins based ALARA dose estimation, the development of an AI/ML model will facilitate the tracking, interpolating and prediction of changes in the radioactive source term during specific decommissioning operations. This model should help keep the digital twin sufficiently accurate so that it can feed essential information into radiation protection and dosimetry systems.

Regarding robot route optimization, AI will be applied rather for leveraging already existing structured data in 3D digital twins for informing robot missions, for optimizing new data acquisitions and planning robot missions based on previous data considering multiple robot platforms and their capabilities for performing data acquisition tasks.

Regarding Voice Assistance Technologie, the use of AI will be integrated. The voice assistant will make use of the ontology to develop smart interfaces with the operators. The goal of voice interactions is to free the hands of the operators at work, reduce the time of their presence in hazardous situations, prevent the contamination risk of documentation devices, and enhance the quality of the data reported onsite.

For the demonstration on real use cases, the creation of a parametric 3D model will be facilitated by the use AI for helping in making the decision on when to invest efforts in it. For decommissioning safety and risks/hazards assessment, AI will be used for structuring information from remote/autonomous characterization based on the DORADO ontology. Legacy information and data related to characterization and past events relevant for decommissioning (Safety Analysis Reports (SARs), Radiological surveys, radiological events, modification of design, inspections, data from radiological monitoring systems, discharges into the environment, etc.). The AI and DORADO ontology will be used to structure the information. Missing information and data in the BIM model will be supplemented with additional data and information coming from the use of AI with remote/autonomous characterization process and employees on-site with the help of the voice assistant technology. Regarding risk/hazards assessment, the recognition of potential risk/hazards is expected to be improved with the help of AI by crossing relevant information using the SIM (Safety Information Model) approach developed in the frame of the previous PLEIADES project. In particular, AI models can analyze historical decommissioning data to predict potential hazards (e.g., radiation leaks, structural instability) and anomaly detection can be enhanced by AI-powered sensors continuously monitoring radiation levels, temperature, and structural integrity, flagging abnormal readings in real time.

Regarding the use of AI for supporting decommissioning, the outcomes of the DORADO project and work packages will help to define the need, the possible application cases and the potential uses for AI in decommissioning field. A special attention shall be made on few critical questions: 1- what is the amount of data needed to train specific AI models for decommissioning to get reliable results, 2-

based on this amount of necessary data, what type of data sharing model can be used to aggregate data from different stakeholders, 3- what type of validation and verification rules need to be implemented to trust the output of such model, 4- finally a deep cost analysis shall be conducted, based on the required infrastructure (shared or dedicated), its exploitation cost and its environmental impact.

In all cases of AI utilization, data security shall be treated with high priority. One of the risks of using AI models is exposing the data to the provider of a certain AI model. Therefore, in DORADO, the ways and approaches how to use AI models (either ML-based or LLM-based) deployed on the project's should be researched and no AI models operated outside of the DORADO's platform should be used.

3 Literature Review and State-of-the-Art Analysis

3.1 Related EU Projects

The Project **PLEIADES** (PLatform based on Emerging and Interoperable Applications for enhanced Decommissioning processES) was funded by the EURATOM (European Atomic Energy Community) program of the European Commission (EC) between October 2020 and November 2023 [8], [9]. Important results were achieved by creating a platform able connecting various digital tools in order to improve efficiency in decommissioning activities. DORADO builds upon PLEIADES, extending its digital twin and ontology concepts for robot-assisted decommissioning operations [10].

CLEANDEM (Cyber physicaL Equipment for unmAnned Nuclear DEcommissioning Measurements) developed a mobile unmanned ground vehicle (UGV) equipped with advanced detection technologies for 3D-localized radiological measurements [11].

XS-Ability (Accessing hard-to-reach areas with Advanced and Breakthrough Innovation for reLiable In-situ characterization of a faciliTY) focuses on developing advanced robotic solutions with embedded sensors for remote investigation of hard-to-access areas and difficult-to-measure radionuclides characterization [12]. Building on CLEANDEM, XS-Ability's innovations in nuclear instrumentation and robotic integration can inform DORADO's approach to robot-assisted decommissioning. DORADO and XS-Ability are running in parallel, with DORADO focusing on the development of AI-based robotic applications for decommissioning operations, while XS-Ability concentrates on creating advanced robotic solutions for investigating hard-to-access areas in nuclear facilities. The synergistic nature of these projects allows for a continuous exchange of knowledge and technological advancements, thereby informing and enhancing each other's progress in the field of robotic applications for nuclear decommissioning and characterization tasks.

CONfigurable CollaborativE Robot Technologies (**CONCERT**) project utilized advanced perception, supervision, and planning tools to enable adaptive shared autonomy and seamless integration of robotics into construction workflows [13]. CONCERT's approach to integrating robotics with flexible, real-time task planning in construction, underpinned by BIM for workspace mapping and coordination, directly parallels DORADO's use of BIM and robotics to enhance safety and efficiency in complex decommissioning environments [14]. Both projects leverage BIM as a central data model to enable adaptive, automated operations.

BIMProve automated the comparison of planned versus actual construction progress, reducing manual inspections and errors, and increasing the efficiency and resource sustainability of construction sites [15]. BIMProve's work on integrating real-time sensor data with BIM to create dynamic digital twins aligns closely with DORADO's use of BIM and digital twins for continuous monitoring, change detection, and adaptive planning in decommissioning operations

HumanTech had a focus on making construction safer, greener, and more efficient by developing digital tools and autonomous systems for planning, progress control, and quality monitoring [16]. HumanTech's focus on autonomous data capture and digital twin generation within BIM directly supports DORADO's vision of using BIM-enabled digital twins, sensor fusion, and automation to improve safety, precision, and data-driven decision-making in hazardous decommissioning contexts.

HARPERS (HARmonised PracticEs, Regulations and Standards in waste management and decommissioning) aims to establish the benefits of more aligned and harmonized regulations, practices, and standards in decommissioning and radioactive waste management [17]. DORADO can benefit from HARPERS' findings on regulatory harmonization to ensure its digital twin and ontology approaches align with evolving standards across EU member states.

The EURATOM **PREDIS** project (2020-2024) targeted the development and implementation of activities for pre-disposal treatment of radioactive waste streams other than nuclear fuel and high-level radioactive waste [18]. The Digital Twin developed in this project is an accessible tool designed to assess and predict the evolution of waste packages. It simulates key mineralogical and mechanical processes affecting package integrity, without requiring full thermal-hydrological-mechanical-chemical (THMC) coupling. By using geochemical and chemo-mechanical models, along with surrogate models like neural networks and lookup tables, it enables efficient analysis of degradation scenarios. Users can run simulations on various waste compositions, including expert-defined reference waste types, helping to fill gaps in existing data. The tool aims to support both legacy and future waste packages, allowing for "what-if" analyses and testing of new materials.

The EURATOM **SHARE** roadmap highlights how technological innovation and improved project management across all phases of decommissioning can enhance efficiency, reduce costs and timelines, improve safety, and minimize waste. It identifies key research and development activities, aligned with a strategic agenda, that can significantly improve future decommissioning efforts [19]. Roadmap diagrams illustrate these activities by importance, urgency, and action type. A timeline, based on stakeholder input, prioritizes urgent tasks by theme and reflects trends like digitalisation, sustainability, and the circular economy, while also emphasizing the ongoing need for training, education, and harmonisation. The roadmap encourages coordinated international R&I efforts and the adoption of innovative technologies.

3.2 State-of-the-Art for the Involved Technologies:

3.2.1 Sensor data mapping with temporal dimension

Sensors on tracked platforms

The indoor positioning of mobile robots and other tracked platforms (e.g. remote-controlled vehicles) is an active research topic and there are a wide range of approaches and sensors that have been tried out for this purpose [20]. There are also already widely available solutions for robot navigation included in open platforms like ROS [21]. Especially SLAM solutions are commonly used for navigating, while constructing a map of the environment at the same time, with sensors like LiDAR, RGB-D cameras, or IMU [22].

Often SLAM and many other positioning solutions provide the location in a local coordinate system, and we may want global coordinates to be able to match the route with existing floorplans or 3D models of the environment. A common approach for this purpose is to start the robot in a predefined position and compare the generated SLAM map to the reference maps or floor plans to prevent the drift. However, there are also some examples where e.g. floorplans can be used directly for global positioning [23]. Recently there have been also methods that align the local point cloud with reference data that has been generated directly from the BIM model [24].

In addition to aligning the robot or other tracked platform on global coordinate system, we need to also calibrate the coordinate transformation between the tracked platform and the additional sensor. In the case where the robot is tracked using an attached LiDAR, we want to in fact calibrate the additional sensors (e.g. cameras) compared to the LiDAR coordinate system. This is commonly done by showing a calibration target (e.g. checkerboard pattern) that can be seen both the LiDAR and the other sensor [25].

Sensors in a calibrated rig with camera

Especially, in case of handheld devices, we assume that additional sensors are attached to a common rig with an RGB camera. This way we can use alignment methods that are suitable for cheap RGB cameras also for all other possible sensors. Making a calibrated rig, where one or several separate sensors which are attached to an RGB camera with known transformation between them is a relatively common practice. For example, [26] use a calibrated rig to superimpose thermal-infrared data on 3D environment.

There are also quite a lot of solutions using image matching with aligned reference images [27]. Similarly, several approaches match local 3D shapes with reference 3D [28]. However, our previously described method of visual localization of camera by matching photos with a 3D LiDAR point cloud is a novel approach. Still, this approach does utilize many state-of-the-art methods that are described below.

Visual Place Recognition (VPR) is a method of recognizing physical location despite significant changes in appearance and/or viewpoint. The images are typically converted to feature descriptors that can be used to query best matching reference images. Some recent VPR solutions include: MixVPR, SelaVPR, EigenPlaces, CosPlace, and BoQ [29].

Dense image feature matchers like RoMA [30] can be used to validate the best reference image matches and to estimate the camera pose using 2D-3D correspondences. Furthermore, modern volumetric data structures like NanoVDB [31] can be used to render RGB image representations from the LiDAR point cloud.

3.2.2 Environment data comparison against BIM

In addition to academic research, several software solutions have emerged to facilitate the comparison of point clouds with BIM models, encompassing both commercial products and research prototypes. Among the commercial offerings, Imerso [32] stands out for its support of the Industry Foundation Classes (IFC) standard, enabling direct integration with a wide range of BIM workflows. ClearEdge3D, another notable solution, requires the use of Autodesk Revit's native environment for point cloud and BIM model comparisons, thereby leveraging the robust modeling capabilities of Revit. Furthermore, FARO, a prominent manufacturer of 3D scanning hardware, has developed its own suite of software tools [33] designed specifically to support point cloud to BIM comparisons, reflecting the increasing convergence of hardware and software in this domain.

Beyond commercial products, several research initiatives have resulted in the development of prototype tools aimed at advancing point cloud and BIM integration. Noteworthy among these are the EU-funded projects BIMprove [15] and HumanTech [16]. While these projects have produced promising prototypes, their tools are not currently available for public use. The BIMprove codebase was primarily developed by a project partner not involved in the subsequent HumanTech project, and it is based on a distinct software architecture. As of April 2025, the HumanTech project remains ongoing, with completion anticipated in June 2025, and no final decision has been made regarding the open-sourcing of its software components. Collectively, these commercial and research efforts illustrate the dynamic landscape of point cloud and BIM model comparison tools, highlighting both the availability of mature solutions and the ongoing development of advanced, potentially open-source alternatives within the research community.

In DORADO, the main progress for the planned work is two-fold: We need a possibility to integrate with the DORADO flow of information. The mission planning and multi-robot scans allow creating sets of point clouds that will be used as basis for the comparison of environmental scans against the BIM. It will also be an input into a semi-automatic flow to update the BIM–model(s) based on the detected changes. Existing commercial products (e.g., Imerso, ClearEdge3D, Faro As-Built) offer important functionalities related to comparing point clouds and BIM models. However, these solutions typically remain proprietary, with restricted access to source code. In addition, they have limited interoperability with semantic web ontologies. Ensuring compatibility and synchronization with the ontology developed in DORADO is crucial.

By aligning BIM models with the project's semantic ontology, relationships, classifications, and properties defined in the ontology can remain synchronized with BIM model content. This alignment not only maintains consistency across multiple digital representations but also allows valuable semantic information embedded in the ontology to be effectively linked with or even directly integrated into BIM models. Such integration can enhance BIM models by providing additional context, richer metadata, and improved semantic depth, making them more valuable to end-users, such as project managers, engineers, and robotic operators. Moreover, this integration enables improved compatibility with existing BIM visualization tools and software, facilitating broader utilization of ontology-driven insights within the Dorado project's digital infrastructure.

Thus, a clear research gap emerges: the lack of a transparent, open-source, and ontology-compatible solution capable of seamless integration into workflows such as the DORADO project's mission planning and BIM updating pipeline.

The work proposed in this project addresses this gap by explicitly developing new, open-access methodologies and tools. Much of the software created will be open source. These solutions aim not only to reproduce essential capabilities but also to extend functionality, increase interoperability, and embed richer semantic information from ontologies directly within BIM-models, thus going significantly beyond what current proprietary software and closed-source solutions offer when it comes to those aspects.

3.2.3 Point-cloud and 3D model change detection

Change Detection is used in many areas like damage assessment (e.g. following natural disasters), documentation of urban development, traffic monitoring, etc. Changes can be referred to one-dimensional (mainly vertical changes) or three-dimensional (changes in all possible directions) [34].

This is also the case of the AEC (Architecture, Engineering and Construction) field, where Change Detection plays a significant role in documenting construction progress. However, the method is not used as much in demolition and dismantling tasks. In these activities, manual methods like visual inspections and measurements have been traditionally performed. With the improvement of various kinds of measuring devices in the last years, information is being more and more digitized, and several steps of the process of change detection are increasingly being automated because data can be stored in databases.

It is possible to detect changes by comparing two or more point clouds corresponding to the same environment in different periods of time. But various steps are needed to prepare accurate information: data acquisition, data processing, and data management. Different aspects are to be considered in each one of these steps [35]:

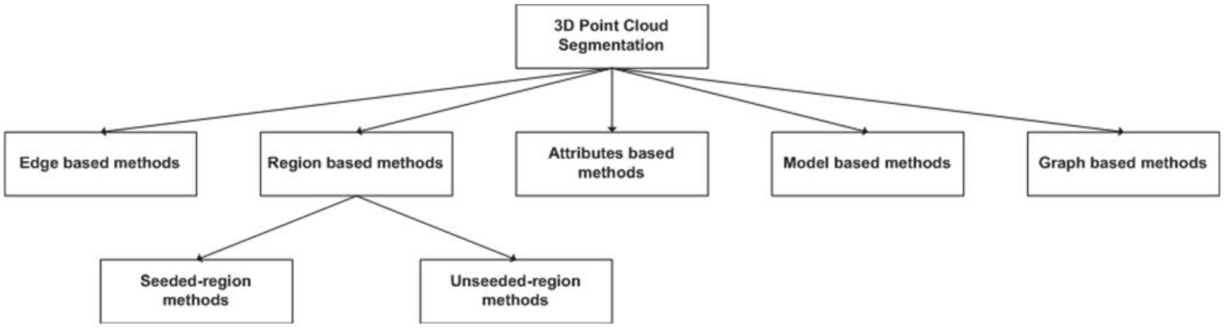

Figure 4: Taxonomy of 3D point cloud segmentation methods [36].

During the data acquisition, the geometry and the properties of the surface are to be considered. These properties will play an important role on the accuracy, so is very important to choose the appropriate method (Laser scanning, photogrammetry, etc.). Different parameters like dimensions and position in coordinate systems may be different depending on it.

When processing the information to generate the point clouds, important parameters may play an important role in the quality of the result: this is the case of noise behavior, point cloud density, or shadow effects among others. Likewise, the input for the processing will depend on the method with which the acquisition is performed. Therefore, data cleaning and preparation is key for having accurate and useful information.

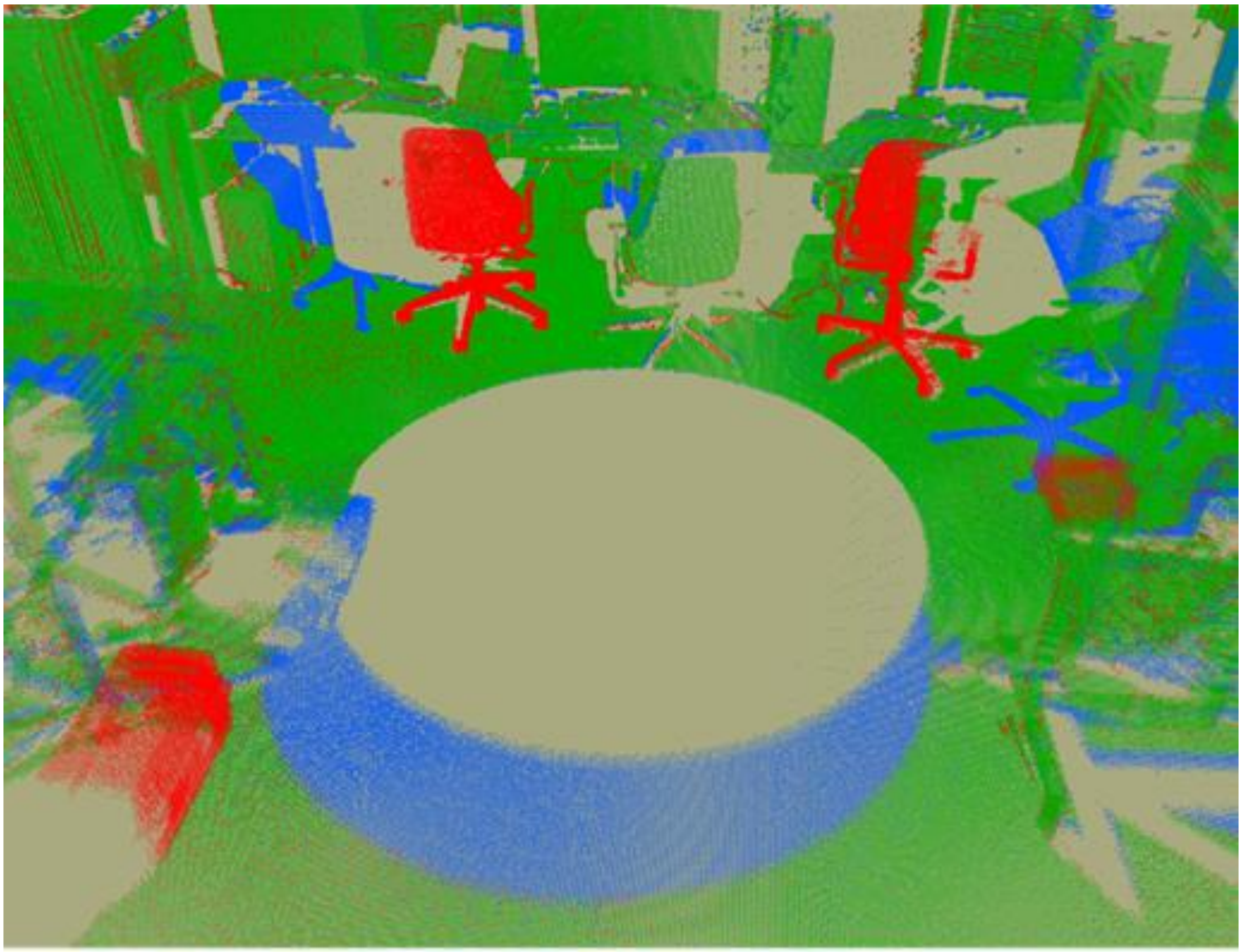

Figure 5: Change detection example with changes highlighted in blue and red colors.

Data management is crucial for the good performance of change detection. Efficient handling, considering files extension (e.g. E57, PTX, ec.) and size (according to the Hardware and Software that is being used) is very important. Point Cloud files are usually heavy files containing millions of points that cannot be displayed by everyone.

Segmentation of point clouds is an important step that facilitates automation of change detection. The literature [36] identifies several methods for the segmentation: Edge based methods, Attributes based methods, Model based methods, Graph based methods or Region based methods. These last ones can be divided in Seeded-region methods and Unseeded-region methods.

Regarding the automation of change detection between point clouds, different methods exist [36]. These are for example Voxel-based analysis, Point-based approach, and Change Detection using ML (Machine Learning).

3.2.4 Digital twins based ALARA dose estimation

The ALARA principle is a foundational component of radiological protection and a regulatory requirement in nuclear operations. It is built upon three key pillars: justification of activities that involve radiation exposure, optimization of protection to minimize exposure, and dose limitation to ensure compliance with regulatory thresholds. In practice, implementing ALARA requires continuous assessment of operational scenarios to identify and reduce unnecessary exposure. Traditionally, such assessments have relied on historical dose records and simplified analytical calculations, often using conservative assumptions to maintain safety margins. While such approaches provide a degree of protection, they may lead to overestimation of risks and result in operational inefficiencies and unnecessary conservatism, especially when used for task planning or resource allocation. Over time, more structured tools were developed, including point-kernel calculators, 3D visualization platforms, and high-fidelity Monte Carlo (MC) transport codes. However, MC tools often lack flexibility for rapid iteration, and typically do not support automatic updates from measurements or geometric changes during dismantling. Furthermore, they require significant expertise to configure and interpret correctly. Their use is not straightforward and is typically limited to very specific cases where detailed and high-fidelity studies are essential. As a result, they are not commonly applied for routine radiation exposure assessments, which demand quick turnaround, intuitive interfaces, and adaptability to changing operational conditions.

In all practical scenarios, radiation protection still heavily relies on dose rate surveys, radiological measurements, and fixed area monitoring systems to capture actual field conditions. These measurements are essential for validating assumptions, adjusting safety zones, and documenting exposure conditions. However, performing such surveys—especially in complex or high-dose environments—can carry considerable dose burdens for the personnel involved. Therefore, optimizing the effort required for surveys and minimizing dose to surveyors is itself part of the ALARA objective. As dismantling progresses and environments change, there is a growing need for integrated solutions that not only support accurate dose estimation but also dynamically adapt to real conditions and optimize protection strategies quickly.

This has led to exploring the development of digital twin-enabled platforms that unify 3D geometric models, sensor inputs, and radiation simulation capabilities into a single, adaptive environment. These platforms aim to bridge the gap between operational planning and radiation protection by enabling simulation, visualization, and optimization of work scenarios under evolving radiological and geometric conditions.

Examples of recent developments of platforms that could be used for ALARA planning include:

- **DEMplus® for nuclear**, from Cyclife Digital Solutions (EDF Group), is a commercially deployed platform that combines physical, radiological, and operational models into a single interface. It enables the simulation of operator tasks, waste management logistics, and dose predictions in a fully navigable 3D twin of the facility. Its dose assessment features allow for iterative planning and real-time scenario evaluation [37];

- **VRdose**, developed by the Institute for Energy Technology (IFE), offers an immersive environment for dose simulation and ALARA optimization. It allows task planning and virtual walkthroughs in radiation environments, supporting intuitive decision-making and enhanced communication among planners, RP officers, and field personnel [38];

- **RADAR**, developed by SCK CEN, is a 3D radiation dosimetry and ALARA planning tool designed to facilitate radiation protection planning and optimization during decommissioning and dismantling activities in nuclear facilities [39].

Each of these platforms addresses specific gaps in traditional ALARA planning: from enhancing spatial understanding to enabling rapid updates during decommissioning phases, and from reducing conservatism in planning to minimizing staff exposure through simulation-driven interventions.

These tools represent a shift from static model-based assessments to integrated, adaptive platforms that support continuous ALARA optimization. Several recent developments could also enhance and automate these platforms with capabilities such as:

- **Photogrammetry, SLAM-based scanning, and sensor fusion**, enabling automated updates to geometry and radiation fields based on robotic or handheld measurements [40];

- **Integration with mobile robotic platforms**, allowing radiological surveys and geometry scans to be performed remotely in high-dose areas, thereby reducing worker exposure [41];

- **Automated scenario comparison**, supporting rapid evaluation of dismantling sequences, shielding configurations, and task schedules with corresponding dose estimates;

- **Interoperability with BIM and CAD ecosystems**, enabling seamless import of as-built geometries and alignment with engineering workflows;

- **Dose heatmap visualization and temporal tracking**, allowing planners to monitor integrated dose along worker paths and over task durations;

- **RADTwin** (under development in DORADO), a machine learning-based predictive model that will estimate radiological source terms and dose fields for different dismantling and handling scenarios. It will use process type, waste category, geometry, historical data, simulations, and dose maps as inputs to support scenario forecasting and source term evolution prediction. This approach builds upon literature showing the successful use of ML surrogates for dose field estimation [42], source term reconstruction [43] , isotope classification [44] , radiation field mapping [45], and predictive localization of contamination [46] ;

- **Immersive training and risk awareness environments**, leveraging game engine-based simulations for enhanced engagement, situational preparedness, and communication [47] ;

- **Regulatory-grade reporting automation**, enabling structured output of dose results, shielding justifications, and ALARA documentation for internal review or licensing submissions.

From a regulatory standpoint, the use of digital twins supports requirements for continuous dose optimization and scenario-based planning. The IAEA's GSR Part 3 [48] and WS-G-5.2 [49] call for repeated reassessment of radiation protection measures during facility changes. Council Directive 2013/59/Euratom [50] enforces ALARA as a legal obligation in EU member states. In the U.S., NRC's Regulatory Guide 8.10 [51] and 10 CFR Part 20 [52] mandate that occupational doses be minimized through effective planning, engineering controls, and informed decision-making.

Recent reports from both the U.S. Nuclear Regulatory Commission (NRC) and Oak Ridge National Laboratory (ORNL) emphasize that digital twins can directly support ALARA and radiation protection planning by enhancing dose estimation, shielding evaluations, and optimization of work sequencing in high-dose areas [53], [54] .

Digital twin-based ALARA planning tools have the potential to improve radiation protection in nuclear decommissioning by providing high-fidelity, dynamic, and scenario-aware modeling environments. Platforms such as DEMplus [40] , VRdose [40] , and RADAR [40] integrate geometry, radiological data, and worker task simulation to support planning, dose visualization, and optimization. These systems also reduce reliance on manual survey efforts, support more informed decisions, and align with international regulatory frameworks.

Within the DORADO project, these capabilities contribute to the broader goal of enhancing dismantling planning using digital twins, data fusion, and AI. As part of this effort, we will explore the integration of RADAR within the overall DORADO framework and develop the RADTwin module—an ML-based predictive tool for estimating evolving source terms and dose impacts. This will support DORADO's objective of building a modular, intelligent system for ALARA-compliant and efficient dismantling workflows.

3.2.5 Server-based integration with IFC file format and extended data queries

Literature overview and state-of-the-art analysis for server-based integration has been approached from three different perspectives:

- Common data environment and its security;
- BIM-based data management frameworks;
- Utilization of IFC file metadata in digital twins.

These perspectives are further elaborated in detail in the following chapters.

3.2.5.1 Common data environment and its security

Nuclear decommissioning planning from its nature works with very sensitive information and thus any data management and digitalization effort must keep the security in mind, as one of the top priorities. This priority rule applies also in the development of common data environment (CDE), which is the backbone of the whole DORADO project. As per [55] every application programming interface (API) that needs to be secured must provide Identity and Access management services, in other words the authentication and authorization. Following research in [56], [57], [58] the OAuth2.0 with JSON Web Tokens (JWT) has been selected as the technology to provide the authentication and authorization layer of security. Main reasons for this selection are maturity of this technology, variety of implementations in different technologies and large community using these technologies.

However, authorization and authentication layer of security is not enough. Also, the transfer of the data between the client and server and backwards must be secured. For this purpose, the standard secured hypertext transfer protocol (HTTPS) using TLS encryption has been selected for the purpose of the DORADO project. This protocol provides encryption of data transferred over the network.

In case of higher security needed, a virtual private network (VPN) tunnel can be established between the client and server. However, for the demonstration purposes of the DORADO project, this has not been found to be important.

3.2.5.2 BIM-based data management frameworks

The DORADO project is highly relying on BIM processes and techniques to bring the platform for 3D-based planning of nuclear decommissioning activities. During the literature review we have found several valuable resources covering utilization of BIM in nuclear decommissioning, namely [59], [60]. However, these resources are discussing different types of nuclear decommissioning activities than activities which will be covered in DORADO project.

Also, we were doing research of resources discussing BIM-based processes in the construction industry. Several interesting resources have been found, for example [61], [62], [63]. However, the research showed that the variety of BIM-based frameworks for digitalization of construction industry is so large that the backwards synthesis of data structures used in these frameworks in order to find common elements, would be very complex and time consuming. Nevertheless, it has become clear that the inspiration by the successful implementations of such frameworks in construction industry may help in specification of DORADO's framework.

Lastly, we've been doing research for a specific part of BIM processes called "BIM for deconstruction" (BIMfD). This specific branch of BIM closely relates to nuclear decommissioning as this can also be understood as a specific deconstruction project. This topic is covered by [64], [65].

3.2.5.3 Utilization of IFC file metadata in digital twins

Currently, the AEC sector lacks tools for digitization, being forced to resort to proprietary software and closed file formats with complex and highly expensive licensing models. [66] The same problem is visible also in nuclear decommissioning. Although, this field is not construction but deconstruction, many common aspects in utilization of open standards as a data backbone of digital twins can be identified. IFC format is an open standard with strong community support. By using this file format at least for storing spatial and non-nuclear data opens new possibilities in development of reusable digital twins. Similar problem is investigated also in construction domain: "However, the construction field currently needs a unified method to build a standardized and universally applicable digital twin model, which is incredibly challenging in construction." [67].

It has also been found that, due to the specificity of nuclear decommissioning domain, some types of data cannot be stored or maintained using IFC files, e.g. radiological measurements. Thus, a specialized common data environment, as it has been presented in previous chapters, must be developed.

3.2.6 Mission control and robot route optimization

3.2.6.1 BIM-based Navigation

The integration of BIM and digital twins is increasingly recognized as a significant advancement for enhancing robot capabilities, particularly in complex and structured environments. BIM offers detailed geometric and semantic representations of operational environments, enabling robots to understand spatial constraints, component relationships, and physical properties. Digital twins further augment this by providing dynamic virtual replicas, facilitating scenario simulation and validation of robotic strategies prior to real-world deployment.

A critical aspect of leveraging BIM for robotics involves the transformation of building data into robot-operational formats. While direct integration of BIM/IFC data is explored, related work demonstrates the conversion of BIM models into formats like Simulation Description Format (SDF) or Linked Building Data (LBD) graphs. This process typically includes extracting component attributes, converting spatial information, establishing semantic relationships using ontologies, and linking activities to specific building components. These transformations are crucial for enabling robots to interpret and utilize the rich information contained within BIM models.

BIM data holds substantial potential for advancing robot navigation. Traditional SLAM-based navigation, while effective in creating geometric maps, often lacks semantic understanding and can be time-consuming. User-defined maps with contextualized semantics offer improved reliability and material classification but require manual effort. Integrating BIM-based digital twins, accessible through formats like RDF graphs and JSON streams, provides a means to enhance navigation accuracy by querying live, semantically rich environmental data. Various data transfer methods are being explored to facilitate this integration, moving beyond traditional IFC-to-URDF conversions and custom ontologies towards more scalable and real-time applicable web-oriented formats like OWL ontology for IFC, JSON versions of IFC, Linked Building Data graphs, and IndoorGML.

Robot navigation fundamentally relies on localization and motion planning. While localization techniques such as scan matching and particle filters, operating on world representations like occupancy grid maps, are well-established, the incorporation of semantic information from BIM can significantly enhance their performance [68]. The shift from purely geometric SLAM maps to semantic maps, often achieved through deep learning-based perception, can be further enriched by the structured geometric-semantic knowledge provided by BIM. BIM models, commonly stored in IFC format and accessible through various encodings (e.g., SPF, RDF, XML, JSON), offer a standardized way to represent building information.

3.2.6.2 Semantic Mapping and Scene Graphs

Recent advancements in semantic mapping and scene graph generation for indoor robotics have demonstrated the effectiveness of layered, SLAM-integrated architectures and ontological reasoning. Hierarchical representations partitioning environments into various levels (e.g., objects, rooms, building levels) have shown significant improvements in accuracy and scalability [69], [70]. The integration of SLAM with semantic object detection has enhanced localization accuracy and mission planning capabilities [71], [72]. The incorporation of pre-defined ontologies and language-based models has further improved spatial relationship encoding and room classification tasks (Bigazzi et al., 2024; Mohrat et al., 2023).

Semantic mapping systems can be broadly categorized into closed vocabulary and open vocabulary approaches [74], [75]. Closed vocabulary systems operate with a predefined, finite set of terms or categories, ensuring high precision and consistency in their outputs [76]. These systems are particularly well-suited for applications requiring high accuracy and safety-critical environments where errors or ambiguities could have severe consequences. In contrast, open vocabulary systems leverage broader, more flexible vocabularies, often supported by advanced models like large language models (LLMs) or embeddings from multimodal frameworks. While these systems excel in handling diverse and dynamic data inputs, they may lack the precision and reliability required for safety-critical tasks due to their susceptibility to semantic drift or overgeneralization.

To enhance the reliability of high-accuracy systems, particularly in safety-critical applications, ontologies can serve as an effective supplement. Ontologies provide a structured framework of domain-specific concepts and relationships, enabling semantic consistency and interpretability. By integrating ontologies with closed vocabulary systems, it is possible to improve both breadth and depth of semantic coverage while maintaining precision.

Moreover, two prominent approaches are object-oriented semantic mapping and scene-oriented semantic mapping (Song et al., 2025).Object-oriented semantic mapping focuses on identifying, localizing, and representing individual objects within an environment, providing a detailed inventory of items that robots can interact with. This approach is particularly useful for tasks requiring precise object manipulation or inventory management. Scene-oriented semantic mapping, on the other hand, aims to categorize and label broader areas or regions within an environment, such as rooms, corridors, or outdoor spaces [77], [78]. This method offers a more holistic understanding of the environment's structure and layout, which is beneficial for navigation and spatial reasoning tasks.

Recent advancements in semantic mapping have led to the development of hybrid approaches that combine the strengths of both object and scene semantic mapping. For instance, some systems now integrate object detection and scene classification to create more comprehensive semantic maps [79]. These hybrid methods enable robots to understand both the overall layout of an environment and the specific objects within it, enhancing their ability to perform complex tasks that require both broad spatial awareness and fine-grained object interaction.

The role of ontologies in several of these studies has been particularly noteworthy. Ontologies provide a structured framework for representing domain knowledge, enabling more consistent and interpretable semantic representations. In the context of semantic mapping, ontologies have been used to define hierarchical relationships between objects, spaces, and concepts, facilitating more nuanced scene understanding. For instance, in approaches like S-Graphs+ and Situational Graphs [80], [81] ontologies help in formalizing the relationships between different semantic elements, allowing for more sophisticated reasoning about the environment. Similarly, in language-extended SLAM systems like LEXIS [82], ontologies play a crucial role in bridging the gap between visual perception and linguistic descriptions, enabling more flexible and human-interpretable semantic mapping. The use of ontologies thus enhances the system's ability to reason about spatial and semantic relationships, improving both the accuracy and utility of the generated semantic maps.

3.2.6.3 Task planning (Muli robot task allocation)

Multi-Robot Task Allocation (MRTA) is a fundamental challenge in multi-robot systems, involving the decomposition of complex objectives into manageable subtasks and their subsequent assignment to robots based on their capabilities and operational status. Task allocation strategies are generally categorized into direct allocation, where tasks are immediately assigned, and delegation allocation, which permits reassignment if initial allocations prove suboptimal [83]. The primary challenge in MRTA lies in optimizing task assignments based on factors such as proximity, capability, and workload, while balancing multiple competing objectives. This requires accounting for system constraints, environmental conditions, and the heterogeneous nature of robotic agents [84].

Various methods exist for coordinating multiple robots to perform tasks efficiently. One set of approaches treats robots as individual agents making decisions based on factors like economic principles or past performance. Market-based algorithms [85], [86] allow robots to bid for tasks based on their capabilities, while reputation systems [87] assign tasks based on a robot's history of success. Competitive models involve teams of robots vying for tasks. Mathematical optimization techniques, like Mixed-Integer Linear Programming, offer precise ways to allocate tasks by considering various constraints and goals, particularly in human-robot collaboration [88]. These methods aim to improve efficiency and reliability in task assignment.

Another set of approaches focuses on enabling robots to learn optimal task allocation strategies or coordinate in a decentralized manner. Reinforcement learning allows robots to adapt their decision-making in dynamic environments through trial and error [89]. Swarm intelligence models, inspired by nature, enable robots to achieve complex coordination through simple local interactions without a central controller [90], [91]. These methods are particularly useful in uncertain or rapidly changing environments, offering scalability and robustness in multi-robot systems.

3.2.6.4 Multi-Robot Route Optimization

Recent investigations have explored several methodologies for BIM-integrated path planning [92], [93]. A foundational approach involves IFC-based layered mapping, where "robot-centric prior maps" are generated by extracting relevant robot properties directly from the BIM model. This enables the development of pathfinding algorithms tailored to specific robot mobility characteristics. Furthermore, the integration of multi-heuristic A* (MHA*) algorithms with Artificial Potential Fields (APFs) derived from BIM's spatial and semantic information has shown promising results, significantly increasing robot object proximity while maintaining comparable path lengths [94]. To address dimensional constraints, sophisticated methods incorporate robot-specific parameters by creating virtual obstacles around physical ones based on robot dimensions, ensuring both navigability and safe operational distances.

The transformation of BIM models into navigable graphs is a crucial step in the route optimization process. Tools like Unity's Navigation Mesh (NavMesh) have been effectively utilized to convert BIM geometry into convex polygons, identifying walkable and unwalkable areas. Alternatively, cross-sections of 3D BIM files can be processed to generate 2D floor maps for path planning implementations. To enhance adaptability in dynamic construction environments, recent research explores the use of LLMs to process textual information embedded within BIM, enabling pathfinding algorithms to dynamically adjust for object avoidance based on the rich spatio-temporal and semantic information available at low computational cost.

For multi-robot scenarios, BIM integration facilitates more advanced coordination mechanisms. Frameworks employing Linear Quadratic Regulators (LQRs) combined with artificial potential fields (APF) have been utilized for collision-free navigation among multiple robots. These approaches can be further enhanced by incorporating spatial constraints derived directly from the BIM model, leading to more accurate and efficient coordinated planning in complex-built environments.

3.2.7 Human to System smart voice assistant interface

Voice user interfaces (VUIs) are becoming increasingly prevalent, yet the studies and literature on the user experience of VUIs are lacking [95]. There is a number of gaps and difficulties in the area of the voice assistance especially in the industrial application field, few of them being the lack of standardized evaluation techniques, the scant attention paid to user variety and context, the absence of guidelines for user-centered design, the accuracy of speech recognition, the handling and recovery of errors, the cross-cultural usability evaluation, and the inclusivity and accessibility considerations [95]. SPIX industry relies heavily on its own research and the 10 years expertise in the domain to carry out its own methodology.

The integration of voice assistants into industrial environments has led to the development of systems capable of monitoring and controlling machinery through voice commands. For instance, a study detailed the design and implementation of an industrial safety system based on the Alexa voice assistant, enabling monitoring of operating parameters and control over motor functions [96].

There are hundreds of chatbot development platforms currently available on the market, most of which are designed for text-based conversational interaction. In contrast, voice bot solutions remain relatively fewer and less mature. This is due to the additional complexity introduced by spoken interaction, which involves challenges in speech recognition, natural language understanding, latency, and the quality of voice capture and transmission in diverse environments.
These solutions can broadly be mapped along two principal dimensions; *turnkey solutions*, which offer ease of use and limited customization, and *toolkits/frameworks*, which provide flexibility and power but require technical expertise for implementation.

Turnkey platforms allow non-technical users to create simple bots quickly and autonomously, often using visual interfaces or drag-and-drop systems. Their main advantages are low entry barriers and short learning curves, making them suitable for small businesses and rapid prototyping. However, these solutions tend to lack integration capabilities with enterprise systems and cannot support complex, domain-specific use cases. Examples include HubSpot Chat Builder (Motion.ai), Botsify and BotNation.ai.
These platforms are generally better suited for marketing or customer service chatbots in relatively standardized domains.

Toolkits refer to extensive libraries and modular frameworks that allow developers to assemble advanced conversational systems—both chat and voice-based. These platforms typically offer custom NLP/NLU pipelines, Machine learning (ML) integration, fine-grained control over dialogue management, and API connectivity to third-party software and databases. Examples include Google Dialogflow, Microsoft Bot Framework, IBM Watson Assistant, Amazon Lex, Rasa (open source), Snips (formerly open source, now acquired by Sonos), and SAP Conversational AI (formerly Recast.ai).
These solutions can support on-premises, hybrid, or cloud deployments, and some are even extensible to voice modalities via integration with ASR (Automatic Speech Recognition) and TTS (Text-to-Speech) engines.

IBM Watson Assistant offers modular, cloud-based AI APIs that can be orchestrated to build powerful conversational agents. However, the implementation complexity, cost, and cloud dependency make it a less attractive option for many industrial applications, particularly those requiring *offline operation* or operating under *strict data governance* [97].
Microsoft Azure Bot Service (formerly CoPilot) offers a comprehensive SaaS-based bot development environment. It supports multilingual and multimodal bots but relies on Microsoft's cloud infrastructure, which introduces challenges for deployment in industrial contexts without consistent network connectivity [97].
Alexa suite (Alexa, Arduino modules, Alexa's sensor, and Alexa's relays) is a solution that can be deployed in certain industrial settings with a high success rate. However, it should also be noted that this system depends directly on the connection, reliability and speed of the internet network to which the assistant, the control, and measurement devices are connected. Highly noisy environment is also an obstacle to using this kind of technology.
Rasa stands out as an **open-source alternative** for building conversational agents. Its architecture supports **domain adaptation and machine learning-based intent recognition**, but the core platform focuses on **text-based interfaces**. Voice interaction must be integrated externally, e.g., by coupling with an ASR system such as Mozilla DeepSpeech or Vosk [97].

3.2.7.1 Sector-specific approaches

Vertical chatbots are pre-packaged solutions tailored to a specific industry or business function (e.g., travel, banking, customer service). While highly effective in narrow domains, they are often **not portable** to new business contexts or industrial scenarios. An example of such chatbots are Destygo and Bottomatik that serve tourism and events industries, respectively.

Voicebot integrators work with a mix of proprietary components and third-party APIs to build customized conversational voice interfaces. These are generally used in **customer service** (e.g., contact centers) and not in **mission-critical industrial systems**. Examples of such voicebot integrators are Eloquant, Zaion, Calldesk, and Dydu.

3.2.7.2 Challenges in industrial VUI implementation

Ensuring usability in voice assistants within industrial settings presents unique challenges. A systematic review highlighted the need for VUIs to facilitate natural human–machine interaction, emphasizing the importance of user experience optimization [95], [98]. Moreover, implementing virtual assistants and voice interfaces in industrial environments entails addressing practical challenges such as ambient noise, user training, system integration, and disconnection from cloud platforms. Research has identified these challenges as critical factors influencing the effectiveness of VUIs in industrial applications [97].

3.2.7.3 Future directions

To advance the deployment of voice assistants in industrial contexts, future development should focus on:

- Enhancing robustness: Developing VUIs capable of operating effectively in noisy industrial environments without cloud reliance. [96], [97];
- Personalization: Tailoring voice assistants to accommodate individual user preferences and regional accents [99];
- Design of commands and language: Future research should investigate language design for VAs further, especially for tasks of higher complexity [97];
- Security and Privacy: Addressing concerns related to data security and user privacy in voice-assisted industrial systems [98].

3.2.8 Standardization using the common ontology

The development of ontologies combines formal methodologies, collaborative practices, and software tools. In the beginning of the process the domain(s) of interest and the intended application of the ontology has to be described and defined. This step ensures that the ontology is relevant and aligned with its use case. A fundamental principle in modern ontology development is the emphasis on reusability. Existing ontologies are to be evaluated for their potential use. By this way already standardized and proven knowledge domains can be integrated efficiently.

Ontology construction follows an iterative workflow that includes the identification of key domain concepts, the design of a class hierarchy (or taxonomy), and the specification of attributes and instances. Two principal methodological approaches guide this process: the top-down approach, which leverages foundational ontologies and formal models, and the bottom-up approach, which draws from existing datasets or legacy materials to derive candidate classes and relationships. Often, a hybrid of these approaches is used to balance rigor and efficiency.

A critical component of ontology development is the choice of representation language. The Web Ontology Language (OWL) is the most prominent standard, offering strong expressive power and support for formal reasoning. For less complex needs, lighter-weight languages such as RDF (Resource Description Framework) and SKOS (Simple Knowledge Organization System) are employed. Ontologies are typically stored as collections of triples—subject, predicate, and object—enabling semantic relationships between concepts. Each class, instance, and property is uniquely identified using a URI (Universal Resource Identifier), which ensures clear referencing and interoperability across systems.

Tool support has significantly advanced in the field, with ontology editors (Protege) and management platforms (Vocbench) now providing visual modeling, consistency checking, and inference capabilities. These tools streamline the construction, validation, and deployment of ontologies, making them accessible even to users with limited formal training in ontology languages.

Ontology development is inherently collaborative and involves multiple roles. Domain experts contribute deep knowledge of the subject area but may not be familiar with formal ontology modeling. Ontology engineers possess the technical expertise needed to build and maintain the ontology, ensuring it adheres to semantic and structural standards. Knowledge workers, such as analysts and decision-makers, use the ontology under operational conditions to support data-driven tasks and problem-solving.

The following topics will be addressed during the ontology development:

- Space and Geometries (connection to IFC);
- Connection to decom core ontology pf the PLEIADES project;
- Risk Management according to ISO 3100;
- Mission Planning;
- Boundary Conditions.

4 Use Cases

This section details four key use cases demonstrating the DORADO platform's capabilities in addressing the specific challenges of decommissioning legacy nuclear sites. These use cases were defined to demonstrate the potential associated with the integration of multiple modules of the platform. Moreover, these use cases were defined while processing the information collected from stakeholders (questionnaire feedback, interviews, etc.) as detailed in D2.3.

4.1 Use Case 1: Intelligent Mission Planning and BIM Integration

- **Scenario:** A decommissioning team receives a high-level mission plan for surveying a specific area within a legacy facility. This plan outlines the objectives, constraints, and expected outcomes of the survey.
- **Technology Application:**
    - The mission plan is used as an input for the platform where, informed by the ontology, the plan is broken down into a series of actionable robotic/manual tasks. These tasks are then visualized in the existing BIM model of the facility (if available in IFC format);
    - If a BIM model doesn't exist or is outdated, the team can first deploy mobile robots (quadruped or wheeled) equipped with LiDAR scanners to perform initial point cloud scans of the area. Manual handheld scanners can also be used for specific areas of interest. Note: This process may be combined with the actual (radiological/safety) survey or can at least provide initial radiological/safety data that can be considered for the actual survey;
    - The robots will utilize SLAM (Simultaneous Localization and Mapping) algorithms to generate real-time maps for autonomous navigation within the environment. These maps also contribute semantic data to the BIM model, such as identifying potential obstacles or structural features;
    - The generated point cloud data is fed into a radiation simulation engine, which uses the spatial information to create a detailed radiation heatmap of the facility, highlighting areas of elevated radiation, components of elevated activity, or other conditions related to safety;
    - Personnel can use voice assistance to provide real-time observations and descriptions of the site during the scanning process. This information, informed by the ontology, is automatically transcribed and integrated into reports associated with the BIM model, enriching the semantic data.
- **Value Proposition:** This use case streamlines the initial survey process, providing a comprehensive and spatially accurate understanding of the site with minimal human entry

into potentially hazardous areas. The integration of mission planning, BIM, robotic scanning, and radiation simulation significantly enhances efficiency and safety from the outset.

4.2 Use Case 2: Precise Localization and Change Detection through Multi-View Scan Registration

- **Scenario:** Over time, multiple scans of the same area within the legacy facility are conducted using robots or handheld devices from various viewpoints. Accurate localization of these scans (within a global coordinate system) and the ability to identify changes over time are crucial for monitoring the decommissioning progress and identifying potential issues.
- **Technology Application:**
  - The platform utilizes advanced sensor data mapping techniques to register point cloud scans from multiple views. This process aligns the different scans with high precision, allowing for accurate localization of future scans within the existing spatial framework;
  - This registration capability can be used with both robotic and handheld scanning devices, providing flexibility for different monitoring needs;
  - By comparing historical scans with newly acquired data, the platform automatically highlights any changes detected within the scanned area. This could include the removal of equipment, structural modifications, or the movement of materials;
  - The ontology helps categorize the detected changes, in the point cloud, and connects them to the facility configuration, allowing for intelligent filtering and evaluation of the identified differences. For instance, this can include detecting radiation levels higher than considered normal for certain areas at certain times, detecting premature changes to systems and components, or detecting unexpected issues like the presence of objects at undesirable locations or in undesirable conditions.
- **Value Proposition:** This use case enables accurate and efficient monitoring of the decommissioning progress, highlighting deviations from the plan and potential safety concerns with reduced manual work. The ability to precisely localize scans is crucial for enabling such long-term semi- or fully automated safety monitoring.

4.3 Use Case 3: Ontology-Driven Reporting and AI-Enhanced Hazard Assessment

- **Scenario:** Decommissioning personnel need to generate comprehensive reports about the state of the legacy/decommissioning site. In this process, there is a need for proactive hazard identification based on the available data.
- **Technology Application:**

- Using voice assistance, informed by the ontology's understanding of the facility and decommissioning processes, personnel can generate detailed reports about specific areas or components of the site with no-, or minimal manual labor;
- The DORADO platform automatically compares the information provided in these voice-generated reports with the existing data associated with the BIM model, identifying any discrepancies or missing information;
- Leveraging AI algorithms informed by the ontology's knowledge of potential hazards associated with different components and conditions, the platform performs an automated assessment based on the generated reports and data in the BIM model;
- If the AI identifies potential hazards or gaps in the data (missing or insufficient quality data to confirm safe conditions), robots can be teleoperated to specific locations to collect the necessary missing information (e.g., detailed visual inspections, radiation mapping close to safety critical components or areas of unknown/uncertain radiological conditions, etc.).

- **Value Proposition:** This use case streamlines the reporting process, ensuring consistency and accuracy by leveraging the ontology. The AI-enabled assessment provides a proactive layer of safety analysis, while the ability to task robots for targeted data collection ensures a comprehensive understanding of potential risks.

4.4 Use Case 4: Autonomous Waste Drum Monitoring

- **Scenario:** Numerous waste drums are stored within a designated area (e.g. interim storage) of the legacy facility. The condition of the waste needs to be regularly monitored including radiation levels and the structural integrity of the drums.
- **Technology Application:**
    - Using the DORADO platform's BIM interface, decommissioning personnel can manually define pre-defined scan points in the waste storage area, guiding the autonomous navigation of robots. Alternatively, the platform can perform analysis based on initial data and automatically suggests more optimal scan points (and hence paths) for comprehensive high-quality monitoring;
    - Robots equipped with radiation sensors (and other sensors, e.g., optical cameras) autonomously navigate to the pre-defined scan points and collect radiation readings, e.g. dose at 1m from the waste drums and at contact;
    - The platform compares the real-time radiation readings from the robots with the expected values from earlier data or assumptions or based on contents and location of the drums (information stored within the BIM model and informed by the ontology);

    - Any significant deviations between the robot's readings and the expected values trigger alerts, indicating a potential issue that requires further investigation.

- **Value Proposition:** This use case enables efficient and autonomous monitoring of waste drums, reducing the need for manual inspections in potentially hazardous areas. The comparison of real-time data with expected values enhances safety allowing for early detection of anomalies (e.g., compromised integrity of waste packages).

Key Performance Indicators (KPIs) and Key Business Indicators (KBIs) serve as vital tools in the evaluation process, providing measurable metrics to track progress and identify areas for improvement. The next two sections introduce KPIs for the system as a whole (referred to as S-KPIs), technology-specific KPIs (referred to as T-KPIs), and cost-benefit analysis. Then, a chain of deductions that starts from setting a target KBI and how it impacts the choice of the S-KPIs and the setting of T-KPIs. Hence, the defined T-KPIs will be further refined during the project to provide evaluation metrics to assess the development of the technologies involved. The results of such assessments will be essential for the upcoming deliverables under WP3. The defined mapping will then help keep tracking and assessing the S-KPIs (and finally the KBIs). Therefore, the mapping will be used both in Top-Down use to steer technical development based on business goals and market needs. But it will also be used for a bottom-up use to track how new developments affect the system and hence the value of the platform. This dual use ensures both strategic direction and operational feedback are tightly integrated for optimal business performance. Aside from the use of the map by technology developers to evaluate the system, regular meetings and workshops should be conducted to do such evaluations across the platform. An enlarged workshop shall be organized by the end of the project to collect internal input and external input from various stakeholders for a realistic assessment and to devise a proper follow-up plan for the commercial products resulting from the project.

5 Business Value Analysis

The primary business drivers for adopting this integrated technology platform in nuclear decommissioning, particularly for legacy sites, are to maximize **safety** and **efficiency** while maintaining a realistic consideration of **costs**, and increasingly, **sustainability**.

Legacy nuclear sites often present a unique set of difficulties:

- Incomplete or Missing Data: Original design documents, operational records, and historical monitoring data may be lost or incomplete, making it difficult to understand the site's past and current conditions.
- Unknown Radiological Conditions: Areas within the site may have undocumented or poorly characterized radiological conditions, posing risks to personnel.
- Difficult and Hazardous Access: Many areas within legacy facilities may be confined, structurally unsound, or have high levels of residual contamination, making human access dangerous and time-consuming.

- Lack of Accurate Spatial Information: Existing maps and drawings may not accurately reflect the current as-built state of the facility, hindering planning and execution of decommissioning activities.

5.1 Key Performance Categories

A robust performance measurement system for nuclear decommissioning requires an approach that encompasses several key dimensions of performance. This report focuses on five critical KPI categories that provide a holistic view of decommissioning progress and success: Safety, Efficiency, Cost, Data & Knowledge Management, and Sustainability.

Safety is the paramount concern in all nuclear activities, and decommissioning is no different. This category focuses on metrics that ensure the protection of workers, the public, and the environment from radiological and industrial hazards. Effective decommissioning must prioritize minimizing radiation exposure, preventing accidents, and maintaining the integrity of containment structures.

Efficiency relates to the optimal use of resources, including time, personnel, and equipment, to achieve decommissioning goals. This category includes indicators that measure the speed and effectiveness of various decommissioning tasks, from initial site characterization to the final dismantling of structures.

Cost is a significant factor in decommissioning projects, which can be very expensive and require careful financial management over many years. KPIs in this category track expenditures, identify cost savings, and ensure that projects are completed within budget.

Data & Knowledge Management is crucial due to the long timescales and the vast amount of information generated during decommissioning. This category focuses on how effectively data is collected, stored, analyzed, and shared to support decision-making, regulatory compliance, and future decommissioning projects.

Finally, **Sustainability** has emerged as an increasingly important aspect of nuclear decommissioning, reflecting a global commitment to environmental responsibility and resource conservation. KPIs in this category track the environmental impact of decommissioning activities, the management of waste, and the efforts to promote reuse and recycling of materials.

These five categories, collectively, represent the core dimensions of successful nuclear decommissioning, encompassing not only the immediate concerns of safety and cost but also the long-term considerations of knowledge preservation and environmental responsibility. A comprehensive KPI framework that addresses each of these categories is essential for ensuring that decommissioning projects are conducted in a manner that is safe, efficient, cost-effective, and sustainable.

5.2 KBIs and S-KPIs for the DORADO platform

To be able to increase the value of the DORADO platform, it's necessary to address the most crucial and active needs of the various stakeholders. This means it's essential to translate the KBI into S-KPIs to make sure the development of the system is addressing the business expectations as it

evolves. The KBIs and S-KPIs were identified by collecting input from technology leads and conducting a workshop with all the partners. The input was analyzed to discuss the system

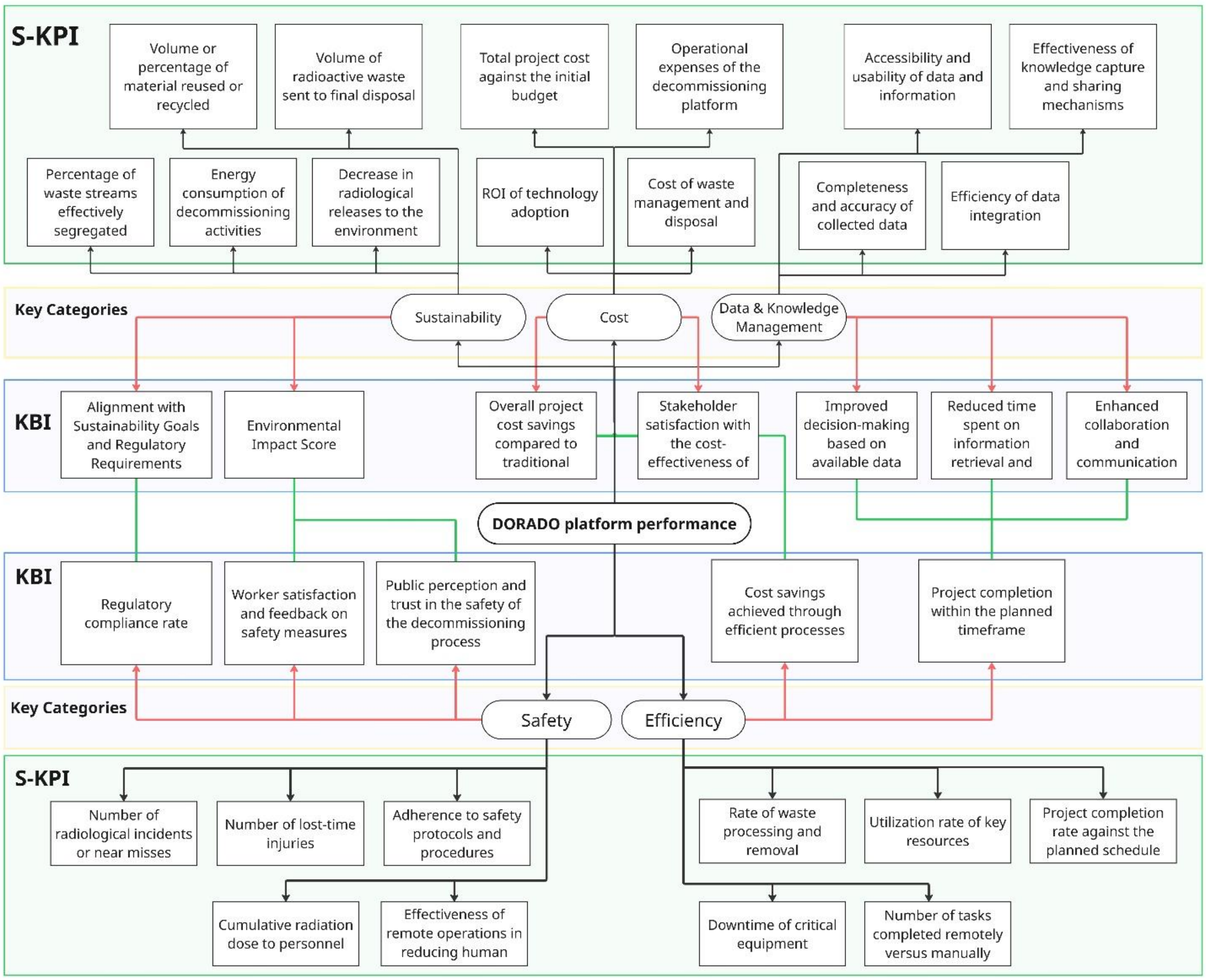

Figure 6: Mapping Key Performance Categories to KBIs as well as S-KPIs.

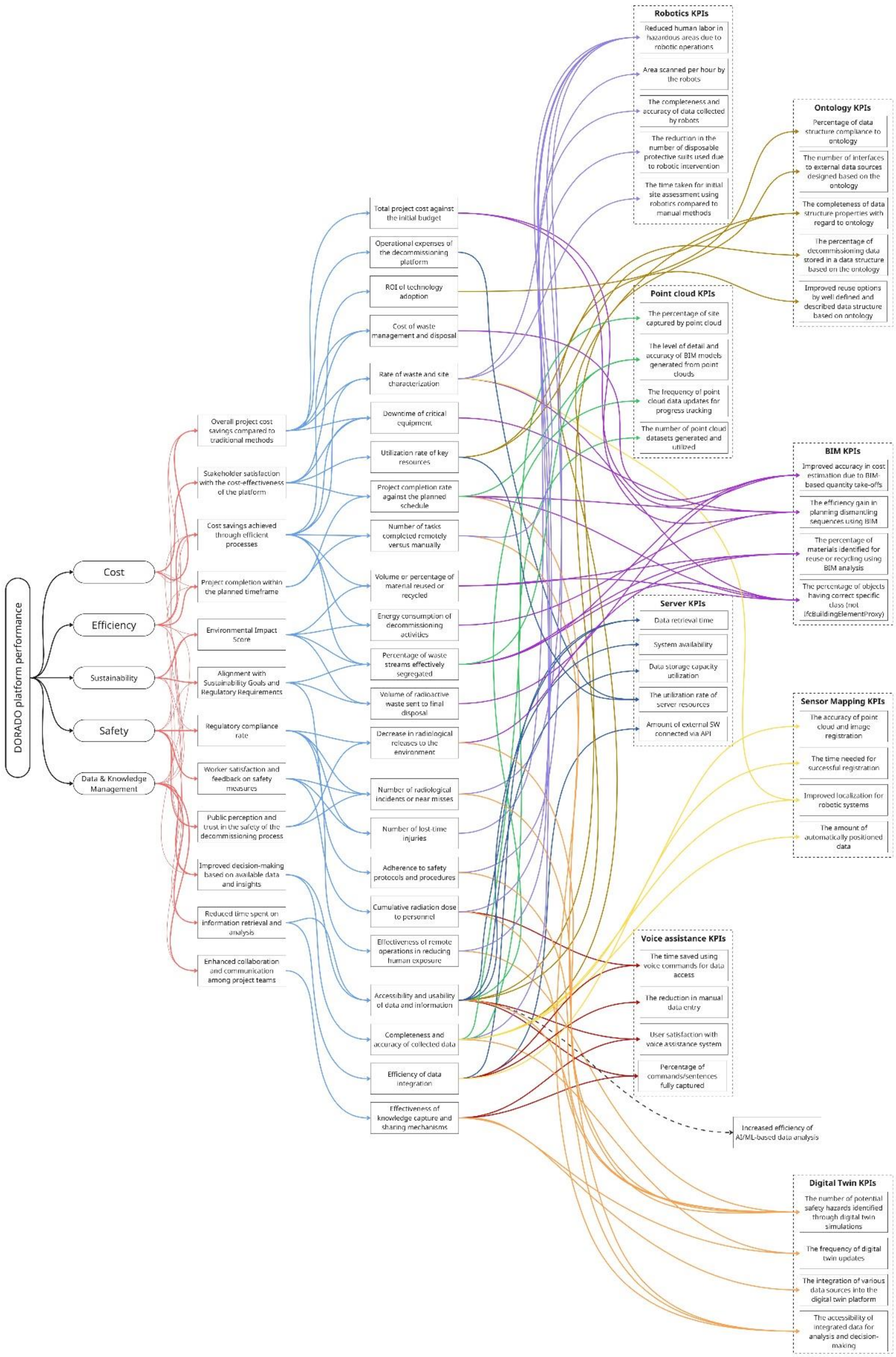

Figure 7: Mapping of key categories to KBIs, S-KPIs and T-KPIs.

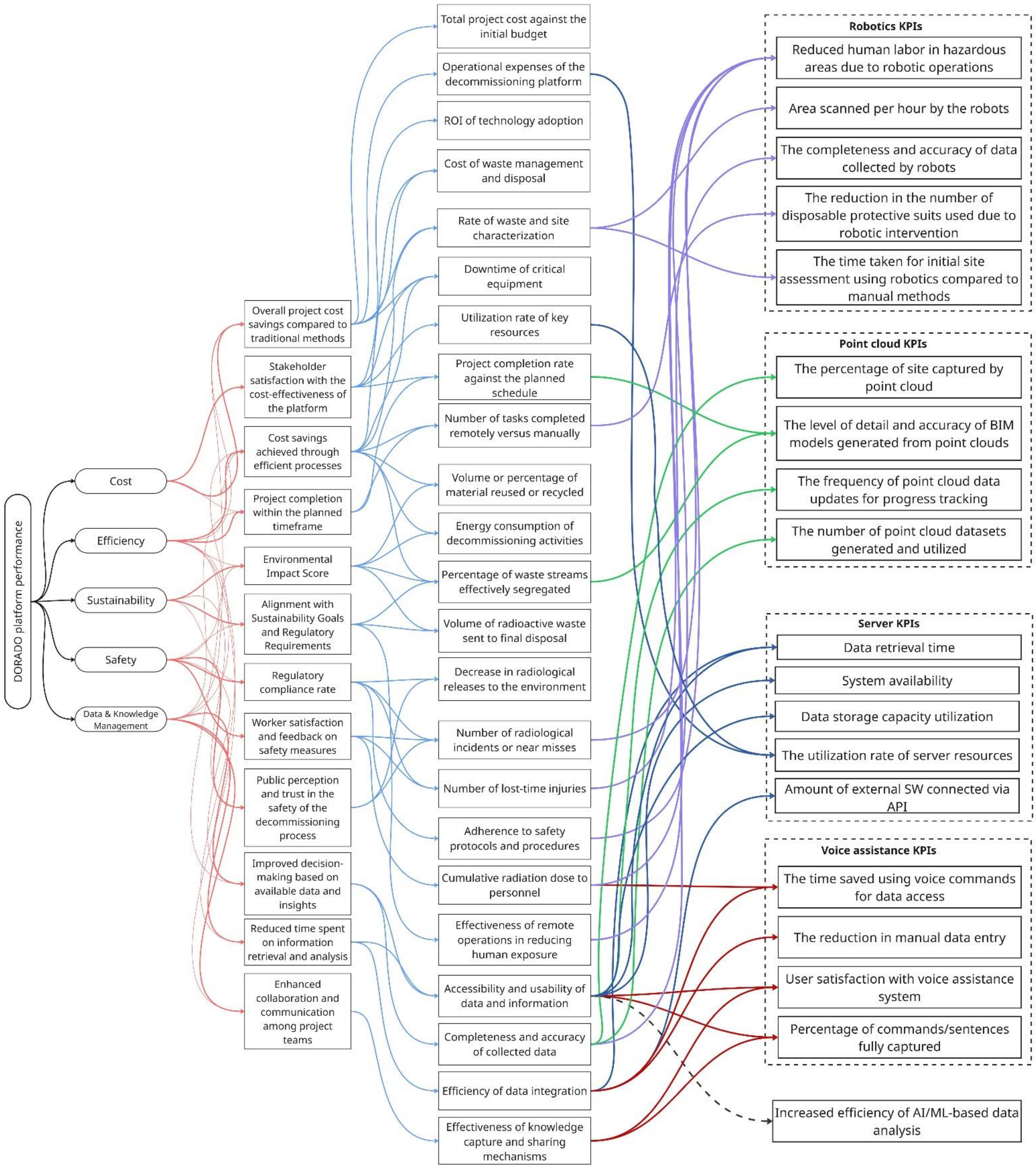

Figure 8: Mapping of key categories to KBIs, S-KPIs and T-KPIs for robotics, point cloud, server, voice assistance and AI for safety assurance.

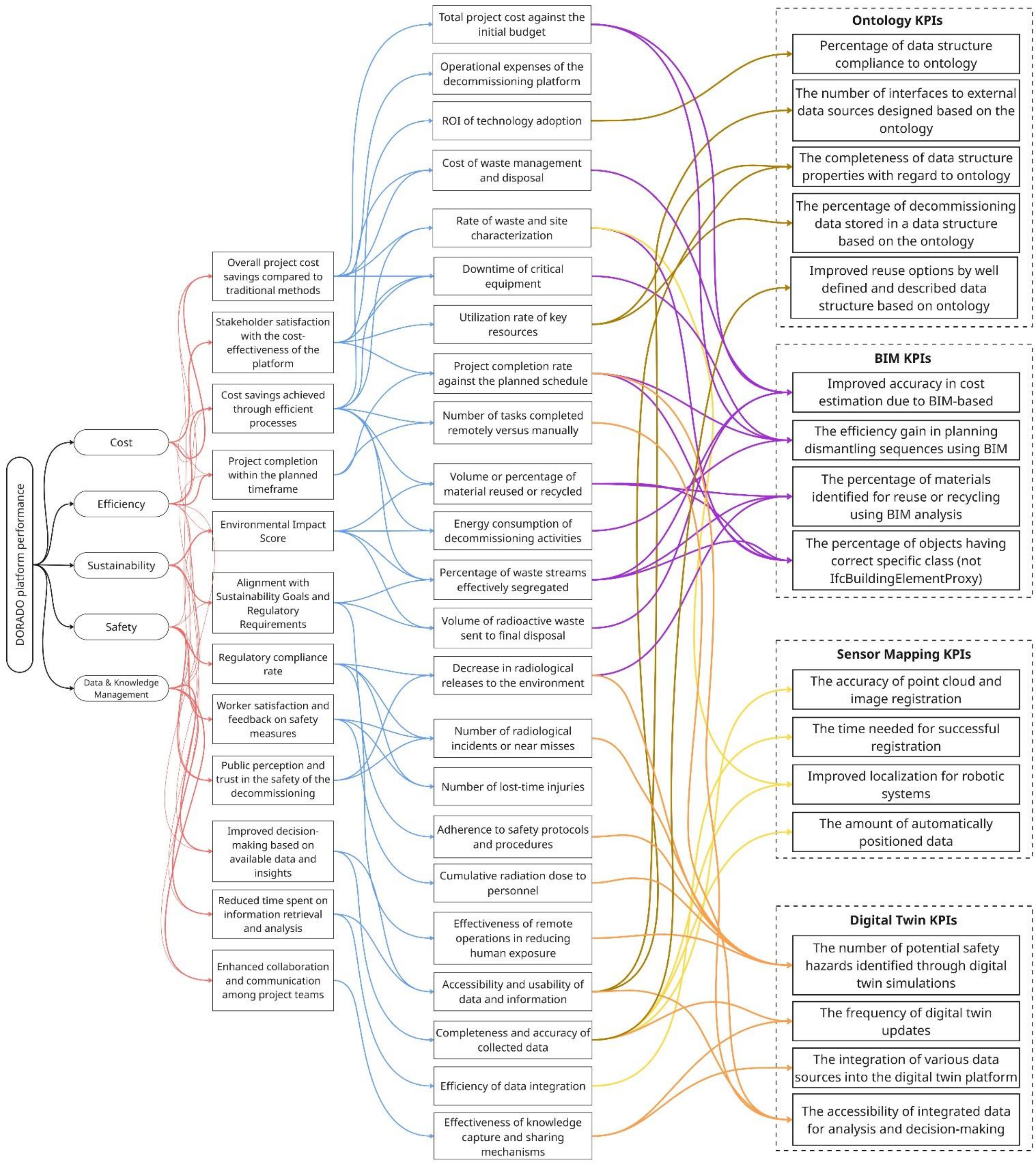

Figure 9: Mapping of key categories to KBIs, S-KPIs and T-KPIs for ontology, BIM, sensor mapping and digital twin technologies.

components and functionalities and the clear mapping and impact on business cases. These were tightly connected to the use cases defined but taking into consideration a wider set of possibilities. The key categories were then mapped to the S-KPIs as well as the KBIs. The developed map is depicted in figure

5.3 Mapping of the T-KPIs for the technology modules in the DORADO platform

While mapping the KBIs and S-KPIs is an essential process, mapping the S-KPIs into T-KPIs ensures staying on the right track in terms of technology modules development. This is crucial, specifically for the DORADO platform, as the system integrates multiple sophisticated technologies with many integration considerations. Hence, having clear development plan per module is necessary to have a parallel development of these modules. As mentioned earlier, the same procedure for mapping KBIs and S-KPIs was followed to map S-KPIs and T-KPIs. The figure xx depicts the developed map drawing the most relevant connections and tight relations between the key performance categories and KBIs, between KBIs and S-KPIs, as well as connections between S-KPIs and T-KPIs. The secondary connections for the key performance categories and KBIs were represented with a light red color while the secondary connections between KBIs and KPIs were neglected to simplify the analysis. Such map allows us to track down the implications associated with the choice of prioritizing some KBIs and how it reflects on the choice of S-KPIs and the T-KPIs.

5.4 Examples of a Chain of Deductions

In this subsection, an example is introduced for each key category showing how KBIs guide selection of S-KPIs and which in turn guides the selection of T-KPIs. Only one or two T-KPIs are highlighted for each example to make it easier to demonstrate the example.

5.4.1 Maximizing Safety

Target KBIs: Improved Worker Safety Record, Regulatory Compliance Rate.

- **Deduction Chain Example 1:**
    - **Target KBI:** Improved Worker Safety Record (fewer radiation exposure incidents).
    - **S-KPI (Safety):** Reduction in Person-Sieverts (collective radiation dose to workers).
    - **T-KPI (Inspection Robotics):** Number of human entries avoided due to robotic inspection (Use Case 1, 3, 4).
    - **System Development Implication:** Prioritize the development and deployment of robust, reliable robots capable of navigating complex environments and equipped with comprehensive sensor suites to minimize the need for human intervention.
- **Deduction Chain Example 2:**
    - **Target KBI:** Regulatory Compliance Rate (adherence to radiation safety regulations).
    - **S-KPI (Safety):** Effectiveness of remote operations in reducing human exposure.

- **T-KPI (Digital Twin):** The number of potential safety hazards identified through DT simulations. This in turn relies on the accuracy of radiation simulation to inform worker safety planning (Use Case 1).
- **System Development Implication:** Invest in the integration and validation of a highly accurate radiation simulation engine that utilizes point cloud data and BIM (mainly IFC) to create reliable heat maps, enabling better planning of remote operations and minimizing potential exposure.

5.4.2 Maximizing Efficiency

Target KBIs: Accelerated Project Timelines, Cost Savings Achieved Through Efficient Processes

- **Deduction Chain Example 1:**
  - **Target KBI:** Accelerated Project Timelines (faster completion of initial site assessments).
  - **S-KPI (Efficiency):** Data acquisition speed for site and waste characterization.
  - **T-KPI (Inspection Robotics and Sensor Mapping):** Area scanned per hour (Use Case 1, 2).
  - **System Development Implication:** Focus on deploying robots with high-speed scanning capabilities and efficient data processing pipelines to rapidly generate point clouds of the facility, accelerating the initial assessment phase.
- **Deduction Chain Example 2:**
  - **Target KBI:** Cost Savings Achieved Through Efficient Processes (reduced manual monitoring costs).
  - **S-KPI (Efficiency):** Number of tasks completed remotely.
  - **T-KPI (Inspection Robotics and AI/ML-based data analysis):** Robot deployment hours for waste drum monitoring (Use Case 4). The AI-based data analysis facilitates increasing the efficiency of the analysis of the collected data.
  - **System Development Implication:** Develop autonomous navigation and scanning capabilities for robots, enabling them to perform routine monitoring tasks like waste drum inspections without constant human supervision, leading to significant labor cost savings. An AI-based analysis is essential then for the analysis of the collected data.

5.4.3 Enhancing Sustainability

Target KBIs: Environmental Impact Score, Alignment with Sustainability Goals.

- **Deduction Chain Example 1:**
  - **Target KBI:** Environmental Impact Score (reduction in waste sent to final disposal).

- **S-KPI (Sustainability):** Volume or percentage of material reused or recycled.
- **T-KPI (BIM):** The percentage of materials identified for reuse or recycling using BIM analysis (Use Case 1, 3).
- **System Development Implication:** Invest in developing advanced features within the BIM module that allow for detailed material analysis and the generation of optimized dismantling plans, minimizing waste generation from the outset.

- **Deduction Chain Example 2:**
    - **Target KBI:** Alignment with Sustainability Goals (increased material reuse and recycling).
    - **S-KPI (Sustainability):** Volume or percentage of material reused or recycled.
    - **T-KPI (Ontology and Server):** Improved reuse options by well-defined and described data structure based on ontology (all Use Cases).
    - **System Development Implication:** Prioritize the development of a comprehensive ontology, reducing redundant data collection efforts and enabling informed decision-making throughout the decommissioning process.

5.4.4 Optimizing Cost

Target KBIs: Overall Project Cost Savings Compared to Traditional Methods, Stakeholder Satisfaction with Cost-Effectiveness.

- **Deduction Chain Example 1:**
    - **Target KBI:** Overall Project Cost Savings Compared to Traditional Methods (reduced surveying costs).
    - **S-KPI (Cost):** Reduction in overall decommissioning costs.
    - **T-KPI (Point Cloud and Robotics):** Cost savings from reduced manual surveying and measurement efforts (Use Case 1, 2).
    - **System Development Implication:** Invest in high-accuracy, high-speed point cloud scanning capabilities for both robotic and handheld devices to minimize the need for expensive and time-consuming manual surveying, leading to significant cost savings in the initial phases.
- **Deduction Chain Example 2:**
    - **Target KBI:** Stakeholder Satisfaction with Cost-Effectiveness (efficient resource allocation).
    - **S-KPI (Cost):** Labor savings through automation.
    - **T-KPI (Voice Assistance):** Reduction in the time taken to complete specific remote tasks using voice interactions compared to manual methods (Use Case 3).

- **System Development Implication:** Integrate a robust and user-friendly voice assistance module that allows for efficient hands-free control of robots and access to information, optimizing operator time and potentially reducing the number of personnel required for certain tasks.

5.4.5 Enhancing Data & Knowledge Management

Target KBIs: Improved Decision-Making Based on Available Data and Insights, Enhanced Collaboration and Communication Among Project Teams.

- **Deduction Chain Example 1:**
  - **Target KBI:** Improved Decision-Making Based on Available Data and Insights (faster hazard identification).
  - **S-KPI (Data & Knowledge Management):** Data retrieval time for critical information.
  - **T-KPI (Ontology):** The completeness of data structure properties with regard to ontology properties and the percentage of decommissioning data stored in a data structure based on the ontology (all use cases).
  - **System Development Implication:** Focus on building a semantically rich and well-structured ontology that allows for intuitive and rapid retrieval of information, enabling faster and more informed decision-making regarding potential hazards and decommissioning strategies.
- **Deduction Chain Example 2:**
  - **Target KBI:** Enhanced Collaboration and Communication Among Project Teams (improved information sharing).
  - **S-KPI (Data & Knowledge Management):** Documentation completeness and accuracy.
  - **T-KPI (BIM and Ontology):** Efficiency in generating and managing decommissioning documentation using BIM and percentage of data structure compliance to ontology (Use Case 1, 3).
  - **System Development Implication:** Invest in a comprehensive BIM platform with features that facilitate collaborative document management, version control, and information sharing among all project stakeholders, ensuring everyone has access to the most up-to-date and accurate information.

6 Cost-Benefit Analysis

One of the main obstacles towards adopting new technologies is the uncertainties regarding the real worth of the investment in the long run. Hence, in this section we break down the costs and highlight the expected benefits and dimensions of such benefits to give a clear image of the expected returns.

6.1.1 Costs

The adoption of inspection robotics, ontology, point cloud, BIM, digital twin, and voice assistance technologies in nuclear decommissioning entails several categories of costs.

6.1.1.1 Initial Investment

This includes the procurement of various types of inspection robots tailored for different tasks within the decommissioning process [100]. Software licenses for BIM, which can range from monthly subscriptions to perpetual licenses, represent another significant initial cost [59]. Similarly, point cloud processing software, digital twin platforms, ontology management systems, and voice assistance solutions require initial licensing fees. The necessary hardware for data acquisition and processing, such as LiDAR scanners, 3D cameras, high-performance workstations, and robust servers, also contributes to the initial capital expenditure. Depending on the specific needs of the decommissioning project, there might be costs associated with customizing or developing bespoke robotic or software solutions [101].

6.1.1.2 Training

A crucial aspect of technology adoption is the comprehensive training of personnel. This includes training on the operation and maintenance of the acquired robots, ensuring that staff can effectively deploy and manage these systems [102]. Training on BIM software and its specific workflows for decommissioning is essential for project planning and management. Personnel will also require training on point cloud processing techniques and analysis to extract valuable insights from the captured data. For effective data management and knowledge sharing, training on ontology development and management is necessary. Utilizing digital twin platforms for simulation and monitoring requires specialized training on the specific platform adopted. Finally, training on the usage and integration of voice assistance systems will ensure that operators can leverage this technology more effectively in their workflows.

6.1.1.3 Maintenance and Support

Ongoing maintenance and support are essential for the continued effectiveness of these technologies. Robotic equipment requires regular maintenance, and in the harsh radiation environments of nuclear facilities, there might be a need for radiation hardening or the periodic replacement of sensitive components [103]. Software updates and the associated support fees for the various software platforms will also contribute to the operational costs. Maintaining and upgrading the IT infrastructure to adequately support these new technologies, including data storage and processing capabilities, is another important cost factor.

6.1.1.4 Integration and Development

Integrating the different technologies and systems to work seamlessly together can incur significant costs [104]. This might involve developing custom software or interfaces to ensure interoperability between platforms. The need for specialized personnel with expertise in multiple technology domains to oversee the integration process can also add to the costs.

6.1.1.5 Operational Costs

The ongoing operation of these technologies will also incur costs. This includes the energy consumption of robots and the IT infrastructure required to support the software and data processing. Personnel costs for the teams operating and managing these new technologies will also be part of the recurring expenses. Furthermore, the storage and long-term management of the large volumes of data generated by these technologies will contribute to the operational budget.

6.1.1.6 Decommissioning Costs of Technology

Finally, the decommissioning of the technologies themselves needs to be considered. This includes the costs associated with the disposal of robotic equipment and hardware at the end of their operational life, particularly if they have become contaminated within the nuclear environment. Long-term data archiving and management costs for the digital assets created during the decommissioning process should also be factored in.

The initial investment in these advanced technologies can be substantial, necessitating a thorough evaluation of the long-term return on investment and the potential for cost savings in other aspects of the decommissioning process. The requirement for specialized training across various technology domains underscores the significance of workforce development and the potential challenges in securing and retaining skilled personnel.

6.1.2 Benefits

The adoption of these advanced technologies offers a wide array of tangible and intangible benefits for nuclear decommissioning projects.

6.1.2.1 Tangible Benefits

Automation and remote operations facilitated by inspection robotics, digital twins, and voice assistance can lead to significant reductions in labor costs by minimizing the need for personnel to work in hazardous areas. These technologies can also accelerate project timelines and lead to faster decommissioning schedules by enabling continuous operation, improving efficiency, and optimizing workflows. A critical tangible benefit is the lower incidence of radiation exposure for workers, as robots perform tasks in high-radiation zones, enhancing overall safety [101]. Optimized waste management practices, supported by BIM and digital twins for better planning and robotics for remote handling, can lead to reduced disposal volumes and associated costs [*]. The precision and accuracy of robotic systems in dismantling and decontamination tasks can improve the quality of work and potentially reduce the amount of waste generated. Furthermore, the use of BIM and ontology can facilitate the identification and segregation of materials suitable for reuse and recycling, contributing to circular economy goals and potentially generating revenue. Improved planning and visualization capabilities offered by BIM and digital twins can minimize errors and the need for costly rework, leading to significant cost savings. The efficiency of inspections, surveys, and data collection is greatly enhanced by the deployment of robotics and point cloud technology, saving time and resources [101].

6.1.2.2 Intangible Benefits

The structured data management provided by ontology and the precise measurements obtained through point cloud and robotics contribute to improved data accuracy and reliability, forming a solid foundation for decision-making. BIM and digital twin platforms enhance collaboration and communication among diverse stakeholders by providing shared digital environments for accessing project information and visualizing progress. The comprehensive data and planning tools offered by these technologies lead to better regulatory compliance and streamline the generation of required documentation. Enhanced data analysis and visualization capabilities within digital twins and BIM enable more informed decision-making throughout the decommissioning process.8 Ontology and digital twins also contribute to improved knowledge management and retention over the potentially long lifecycles of decommissioning projects [101]. The immersive simulations and realistic visualizations provided by digital twins and voice assistance can lead to an improved safety culture and heightened risk awareness among personnel. Finally, the increased transparency and efficiency offered by these advanced technologies can potentially lead to greater public acceptance of nuclear decommissioning efforts.

The tangible benefits of reduced labor costs and accelerated project timelines hold the potential for substantial overall cost savings in nuclear decommissioning projects, which can offset the initial technology investments. The intangible benefits, such as enhanced data accuracy and improved collaboration, contribute to a more robust and efficient decommissioning process, indirectly leading to better cost control and risk management.

For the DORADO platform, many benefits, especially those related to safety and long-term liability, are challenging to quantify precisely. While precise probabilistic evaluations may be limited at this stage, the following approaches can be incorporated:

- **Qualitative Risk Assessment:** For benefits and costs that are difficult to quantify, a detailed qualitative description of their potential impact and likelihood should be provided. For instance, the benefit of "Reduced Human Exposure" might not have a direct monetary value immediately, but its critical impact on safety and reduced long-term liabilities can be qualitatively emphasized as paramount.
- **Sensitivity Analysis:** A sensitivity analysis can be conducted on key quantitative assumptions. By varying critical parameters (e.g., estimated project timeline reduction, assumed reduction in incident rates, cost of specific equipment) within a plausible range, the robustness of the cost-benefit conclusions can be assessed. This reveals how sensitive the overall ROI is to uncertainties in individual inputs.
- **Scenario Planning:** Each of the defined scenarios can define different assumptions for costs, benefits, and the likelihood of achieving certain outcomes, providing a spectrum of potential results rather than a single point estimate.
- **Expert Elicitation:** This involves systematically gathering and synthesizing the judgments of domain experts (e.g., robotics engineers, radiation protection specialists, decommissioning project managers) to estimate probabilities and magnitudes of costs and benefits where empirical data is scarce.
- **Emphasis on Data Collection for Future Phases:** The report should stress that pilot deployments and initial operational phases are not just about achieving objectives but also about systematically collecting empirical data. This collected data will be essential for refining and validating the cost/benefit models for subsequent, larger-scale implementations, moving from qualitative assessments towards more data-driven probabilistic analyses over time.

The table below summarizes the cost and benefits, nature (tangible/intangible), and quantifiability (high/medium/low):

Category	Description	Nature	Quantifiability	Notes/Assumptions
Costs				
Initial Investment	Procurement of robotic platforms, sensors (Lidar, gamma cameras), AI/ML software licenses, computing infrastructure.	Tangible	High	One-time investment.
Development & Integration	Custom software development (e.g., data fusion), system integration, calibration, testing.	Tangible	Medium	Project-specific, dependent on complexity.
Training	Personnel training for operation, maintenance, data analysis, and regulatory compliance.	Tangible	High	Ongoing, but higher initially.
Maintenance & Support	Ongoing upkeep of hardware (robots, sensors), software updates, technical support.	Tangible	Medium	Annual recurring cost.
Regulatory Compliance	Costs associated with obtaining approvals, documentation, and specific safety certifications.	Tangible	Medium	Potentially high initial, then recurring.
Benefits				
Reduced Human Exposure	Decreased need for human entry into hazardous zones, lowering radiation dose uptake and incident rates.	Intangible	Medium	Directly impacts worker safety, health liabilities.

Accelerated Decommissioning	Faster mapping, characterization, and potentially remediation due to robotic efficiency and data-driven insights.	Tangible	Medium	Leads to reduced project duration and associated overheads.
Improved Data Quality	High-resolution spatial and radiological maps, precise characterization, supporting better decision-making.	Intangible	Medium	Enables optimized waste segregation, reduced rework.
Waste Volume Optimization	More accurate characterization allows for precise segregation of radioactive waste, potentially reducing disposal volumes.	Tangible	Medium	Directly impacts disposal costs.
Enhanced Safety Culture	Adoption of advanced technologies for a proactive safety environment and public confidence.	Intangible	Low	Supports long-term organizational reputation.
Reduced Long-Term Liability	Minimized risk of future incidents or environmental contamination due to thorough cleanup.	Intangible	Low	Difficult to quantify financially, but highly significant.

Table 1: List of some of the costs and benefits in relation to the deployment of the DORADO platform.

6.1.3 Return on Investment (ROI):

A simplified framework for calculating the Return on Investment (ROI) for adopting these technologies in nuclear decommissioning can be expressed as:

ROI = (Total Benefits - Total Costs) / Total Costs * 100%

The key cost drivers to consider include:

- **Initial Investment:** The upfront expenses for procuring robots, software licenses, and necessary hardware.

- **Training Costs:** The expenses associated with training personnel to operate and maintain the new technologies.
- **Maintenance and Support Costs:** The ongoing costs for maintaining robotic equipment, software updates, and IT infrastructure.
- **Integration and Development Costs:** Expenses related to integrating different technologies and developing custom solutions.
- **Operational Costs:** The recurring costs for energy consumption, personnel operating the technologies, and data management.

The key benefit drivers include:

- **Reduced Labor Costs:** Savings achieved through automation and remote operations.
- **Savings from Faster Project Timelines:** Cost reductions due to the accelerated completion of decommissioning phases.
- **Avoided Costs from Radiation Exposure Incidents:** Savings from preventing accidents and minimizing health-related expenses.
- **Savings from Optimized Waste Management:** Reduced costs associated with waste processing, storage, and disposal.
- **Reduced Rework Costs:** Savings from improved planning and accuracy, minimizing errors and the need for rework.

It is crucial to recognize the long-term nature of nuclear decommissioning projects when calculating ROI. The benefits of technology adoption might accrue over several years, necessitating a long-term perspective in the financial analysis. Furthermore, conducting a sensitivity analysis by considering various scenarios and potential fluctuations in costs and benefits can provide a more robust understanding of the potential ROI.

The previous description covers a simple ROI which often fails to capture the full spectrum of benefits. [105] offers a robust framework that goes beyond direct financial calculations to provide a more holistic understanding of value. It was argued that the benefits of complex Information and Communication Technology (ICT) systems, such as Enterprise Resource Planning (ERP) systems, are multi-dimensional and not solely confined to easily quantifiable financial gains. The study developed a comprehensive framework that classifies benefits into five distinct dimensions:

1- **Operational Benefits:** These are tangible benefits directly linked to the efficiency and effectiveness of core business processes as described above. For the DORADO platform, an example is the precise characterization achieved by robotic mapping, leading to optimized waste segregation and reduced decontamination efforts, directly impacting project costs and timelines.
2- **Managerial Benefits:** These are often less tangible but crucial for effective management. They relate to improved decision-making, better resource management, enhanced planning capabilities, and improved performance measurement. For the DORADO platform, an example is the improved decision-making capabilities derived from real-time radiation mapping and simulations, allowing for adaptive strategies in uncertain conditions.

3- **Strategic Benefits:** These benefits contribute to the organization's long-term competitive position and growth. For the DORADO platform, this includes enhanced safety culture, reduced long-term liabilities, and improved regulatory compliance, which are crucial for responsible management of nuclear legacy sites.
4- **IT Infrastructure Benefits:** These focus on the improvements to the underlying IT infrastructure itself. This includes building a more flexible and robust IT foundation, reducing IT costs, and enhancing the overall capability of the IT systems to support future changes. For the DORADO platform, this includes the development of robust data management systems and simulation platforms that can be reused for future decommissioning projects.
5- **Organizational Benefits:** These address the impact on the organization's human capital and culture. Examples include facilitating learning and knowledge sharing, empowering employees, and building common visions.

6.1.4 System Failure Risk and Robustness

It is vital to acknowledge that any reliance on advanced technological systems introduces the risk of system failure. Should the platform experience a significant hardware malfunction or a critical software bug, it could indeed necessitate pausing operations, troubleshooting, or even temporarily reverting to conventional, potentially more hazardous or less efficient, decommissioning methods. This could lead to increased project costs, extended timelines, and elevated risks for personnel.

While a detailed treatment of specific failure scenarios and safety management protocols will be elaborated in the deliverable 2.2, it is appropriate to state in this chapter that mitigating these risks is a core design principle. The strategic integration of robust design principles, built-in redundancy for critical components (e.g., multiple sensors, backup communication systems), and rigorous verification and validation processes for both hardware and software are paramount. The aim is to achieve a level of system reliability that not only minimizes the probability of failure but also ensures safe fallback procedures are in place. Furthermore, the design must consider ease of maintenance and rapid recovery strategies. Regulatory authorities will naturally require strong evidence of system robustness and reliability before approving full-scale deployment, and the ongoing development efforts are specifically geared towards meeting these stringent requirements.

7 High-Level Implementation Plan

Adopting these advanced technologies for nuclear decommissioning should follow a structured and phased implementation plan to minimize risks and maximize the potential benefits. The initial steps include forming a dedicated cross-functional team comprising experts from decommissioning operations, IT, engineering, safety, and regulatory affairs. This team's composition should also extend to include representatives or direct channels for feedback from key stakeholders, such as customers (e.g., the site owner or end-user of the decommissioned asset) and external partners (e.g., specialized vendors, research institutions, or other collaborating entities). This broader representation ensures that the technological solutions developed are not only technically sound but also align with the strategic objectives and practical needs of all involved parties. This team will be responsible for overseeing all aspects of the implementation process.

A detailed assessment of the current infrastructure, including IT systems, communication networks, and existing equipment, should be conducted to identify specific needs and gaps that the new technologies need to address. Based on this assessment and a thorough understanding of the most pressing decommissioning challenges, the team should prioritize the adoption of specific technologies that offer the highest potential ROI and align with the project's strategic goals.

Pilot projects should be developed for the selected technologies in controlled environments or specific, well-defined areas of the decommissioning site. These pilot projects will serve as a testing ground to evaluate the performance, integration capabilities, and overall effectiveness of the technologies in a real-world setting. Clear performance metrics and evaluation criteria should be established before the commencement of the pilot projects to objectively assess their success.

Comprehensive training programs tailored to the specific technologies being piloted should be provided to the personnel involved, ensuring they have the necessary skills and knowledge to operate and manage the new systems effectively. Robust data management and cybersecurity protocols must be developed and implemented from the outset to ensure the integrity and security of the data generated and processed by the new technologies. Early and proactive engagement with regulatory bodies is crucial to ensure that the technology adoption plans align with all applicable regulations and to address any potential concerns or requirements. The lessons learned from the pilot projects, including successes, challenges, and best practices, should be carefully documented and used to refine the overall implementation plan.

Crucially, securing strong support of top management is vital for the success of this change and implementation. This support isn't just about financial backing; it involves active championing of the initiative, clear communication of its strategic importance across the organization, and removal of potential organizational roadblocks. Regular briefings for senior leadership on progress, challenges, and the tangible benefits demonstrated in pilot projects will help maintain their commitment. Their visible endorsement ensures that the necessary resources are allocated, inter-departmental cooperation is fostered, and the cultural shift required for adopting new technologies is embraced throughout the organization. Based on the outcomes of the pilot projects, the adoption of successful technologies can be gradually scaled up across the entire decommissioning project, ensuring a smooth and effective transition to a technology-enabled approach.

8 Conclusion and Recommendations

The business case analysis provides the logic, tools and methods that can be used to test and prove the assumed costs and benefits. for the adoption of inspection robotics, ontology, point cloud, BIM, digital twin, and voice assistance technologies for nuclear decommissioning. These technologies offer significant potential to overcome the limitations of current practices by enhancing safety, improving efficiency, reducing costs, and enabling more informed decision-making throughout the decommissioning lifecycle. This report provides the some of the selected KBIs and KPIs that can be used to provide constant measures to follow the realization of anticipated cost-benefit balance.

Based on this analysis, it is recommended that the organization proceed with a phased adoption of these advanced technologies, following the high-level implementation plan outlined in this report. This approach will allow for a controlled and iterative integration, minimizing risks and maximizing the potential for success. A suggested roadmap for technology adoption includes:

- **Phase 1:** Form the cross-functional team and conduct a comprehensive assessment of current infrastructure and needs. Prioritize the technologies with the highest potential impact and ROI for initial pilot projects.
- **Phase 2:** Develop and execute pilot projects for the prioritized technologies in controlled environments, focusing on specific decommissioning challenges. Establish clear performance metrics and evaluation criteria.
- **Phase 3:** Invest in comprehensive training programs for personnel involved in the pilot projects and develop robust data management and cybersecurity protocols. Engage with regulatory bodies to ensure compliance.
- **Phase 4:** Document the lessons learned from the pilot projects and refine the overall implementation plan. Gradually scale up the adoption of successful technologies across the decommissioning project.
- **Phase 5:** Continuously monitor and evaluate the performance of the adopted technologies, adapting the implementation plan as needed to optimize their effectiveness and ensure sustained benefits throughout the decommissioning journey.

The adoption of these advanced technologies represents a strategic investment in the future of nuclear decommissioning, potentially paving the way for safer, more efficient, and ultimately more sustainable practices.

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