A DIGITAL TWIN FRAMEWORK FOR CONSTRUCTION AND OPERATION OF THE RADIOACTIVE WASTE REPOSITORY

by

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The digital twin is considered the central component of modern industry. It has been adopted in many industrial fields. However, its application in nuclear engineering is very rare, especially for the radioactive waste deposits which is an urgent and tricky issue. Motivated by this demand and considering China's research & development guidelines for geological disposal of high-level radioactive waste (a three-step strategy by 2050 to construct the radioactive waste repository), a framework of the radioactive waste repository digital twin is proposed. The digital twin uses the framework *edge + cloud* with a multi-layer structure. It can be adopted in the construction of the radioactive waste repository. It can significantly strengthen the management capability, reduce the operating cost, improve the safety level and deal with accidents more efficiently. The first step for the achievement for the digital twin development of radioactive waste repository based on the framework is also introduced in the paper. The proposed digital twin framework of the radioactive waste repository in this work could be widely used as a reference and easily extended to support management in other industrial fields.

Key words: digital twin, radioactive waste repository, artificial intelligence, building information modeling, case study

INTRODUCTION

Artificial intelligence (AI) and big data have played increasingly crucial roles in the nuclear industry, supporting the design of new and more advanced installations. They are considered as potential technical solutions that can evaluate the data of nuclear libraries [1], realize the thermal-hydraulic model optimization of best estimate codes [2], and develop the safety strategies for the Nuclear Power Plant (NPP) accidents [3, 4], *etc*. With the development of the digital twin, the integration of the nuclear industry with relevant AI technology will be closer, which will cover the whole industrial chain from the fabrication of nuclear fuel to the disposal of spent nuclear fuel. This work concentrates on the use of the digital twin for the radioactive waste disposal since it is thought of as an urgent and tricky issue. The early generation of NPP and relevant nuclear facilities are gradually going out of service. It is reported that around 300 nuclear facilities will be decommissioned around the world in the next 20 years [5].

The management of radioactive waste is one of the most pressing problems all over the world nowadays from both the scientific and the political points of view [6]. Except for the low-level radioactive waste which is on-ground or near-surface disposed, the middle-level and high-level radioactive waste should be geologically disposed of in China with different depths according to the radioactive intensity and decay period of the waste. Based on the current technological limitations, the high-level radioactive waste is normally stored underwater or ground with sufficient radiation shielding structures to minimize the radioactive hazard [7]. Moreover, the facilities need to keep structural integrity for hundreds or thousands of years. It is a challenging task since the storage facilities age and the radioactive wastewater may be produced constantly among the storage, which needs to remove radioactivity before discharge into the environment. As a result, research on deep geological disposal has been conducted since 1985 in China. The official guidelines R&D guidelines for geological disposal of high-level radioactive waste were issued jointly by several government departments, including the China Atomic Energy Authority, the Ministry of Science and Technology and the Ministry of Environment Protection [8]. The Guidelines consisted of a three-step strategy for high-level radioactive waste, involving the site selection before 2020, the underground in-situ tests before

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2040 and the construction of the repository before 2050 [9]. Wang *et al*. [10] introduced the detailed progress in 2018. The final underground research laboratory for high-level radioactive waste has been selected at Beishan in the Gansu Province of northwestern China. Construction of the Beishan laboratory began on June 17, 2021 [11].

Since the underground environment and the related process of facilities are interlinked and complex with a certain uncertainty, it may lead to abnormal occurrences or severe accidents. Moreover, the use of modern technology, *e. g*., remote handling equipment, increases the complexity of handling in the underground laboratory or repository. A challenging issue to the underground facilities is how to introduce an advanced and powerful tool to manage the whole complex project along its life cycle, from its design, construction, operation to closure. Consequently, advanced digital technologies are suggested to deal with these things [12].

The adoption of the concept of the digital twin in the traditional industry is fairly novel. The digital twin in the nuclear industry, *e.g*., in the field of radioactive waste disposal, is still in nascent stages. The application of the digital twin could bring remarkable benefits to the decommissioning of nuclear facilities and storage installations in several aspects: reducing process risks of the related operation, improving reliability and safety, reducing the cost, *etc*. But it is also challenging owing to the dynamic nature and large uncertainty of the process. It involves multi-scale and multi-physics phenomena within a huge temporal span [13]. Although some descriptions of digital twin frameworks can be found in the open literature [14, 15], there are relatively few digital twin frameworks developed specifically for radioactive waste disposal and storage installations. In this work, a prototype framework of the digital twin has been developed to support the management of the radioactive waste repository (RWR). The framework is based on the concept of building information modeling (BIM), which is a relatively mature technology, and the artificial intelligence (AI) innovation platform of the company Jinyuyun, which has been applied in several fields such as grid and power facilities.

Compared to the literature, the main contribution of this paper is to apply the digital twin technology in the field of radioactive waste deposits and develop the framework for the RWR. The framework is crucial for the establishment of future research programs. The detailed structure and methods (including big data technology and machine learning algorithm, *etc*.) are not the focus of this work.

TWO FUNDAMENTAL CONCEPTS

Nowadays, the world is undergoing an era of digital transformation, which is an irreversible change. During the transition, it is common to hear many popular concepts (such as Industry 4.0, AI, the internet of things (IoT), big data and machine learning, *etc*.). These concepts are also applied and widely used in industrial engineering. In this section, two fundamental concepts (*i.e*., the building information modeling (BIM) and digital twin) will be introduced, which are deduced from the above-mentioned concepts and related to the radioactive waste disposal and storage installations from the literature point of view and the objective of this work.

Building information modeling

The basic idea of BIM is the management of a built facility along with its whole lifespan by the assistant of digital building models. It can reduce the laborious and error-prone manual entering of information, increase work efficiency, provide a platform for automated analyses, and benefit the stakeholders for decision making since it supplies an improved information flow at all stages. Although BIM is based on the visualization of a 3-D geometrical model, it involves nearly all the aspects of the modern architectural concept with a high level of intelligence in its lifecycle. It emphasizes the information exchange among the relevant systems or platforms and analysis applications based on the information databases throughout the building lifespan. Recently, BIM has been considering not only the structures, systems, and component (SSC) of the building but also the external environment, notably the carbon emissions [16]. The BIM has already been in practice all over the world owing to its various superiorities compared with conventional paper-based workflows. It was also adopted in the field of NPP decommissioning and the activities (design, construction, operation, closure) related to the radioactive waste disposal facilities [17].

Comparing BIM with the digital twin which will be introduced, one difference between them is that BIM relates to the management of the building during its lifespan while the digital twin involves a couple of hardware elements and their combination [18]. Some scholars predictably pointed out that the transition from BIM to the digital twin is an irreversible trend and the transition is a shortcut and an effective method to realize the digital twin owing to the good technological foundation [19]. Consequently, the digital twin framework developed in this work could be considered as an extended application of BIM.

Digital twin

The earliest prototype of the digital twin in the industry originated from the era of the National Areonautics and Space Administration (NASA) Apollo project in the USA. The formal concept of the digital twin can be traced back to 2003 when Professor Grieves of the University of Michigan showed the industry how to carry out product life-cycle management. He proposed two systems, namely a physical system and virtual system [20]. But as an early stage of its development, a uniform definition of the digital twin is currently impossible among the whole industry currently since a wide range of disciplines are interested in it and this causes differences in the understanding and application of the digital twin. Therefore, instead of discussing the definition of the digital twin, this article is more willing to elucidate the characteristics of the digital twin based on the literature [21].

The main characteristics of the digital twin can be summed up as follows:

– *Real-time reflection*

This is the most fundamental characteristic of the *digital twin* and also its origin. Based on the online smart monitoring system and the simulation of reliable software, the physical object can be reflected synchronously by the digital model with high fidelity. The digital object can be thought of as the 3-D image of the physical object in the mirror.

– *Interaction and convergence*

It is stated that the physical object in the real space, the digital object in the virtual space and the connections between them are considered to be the three basic elements of the digital twin [22]. Some researchers put forward the five elements of the digital twin, introducing data and service additionally [23], as shown in fig. 1. The figure could reflect the connections among the elements clearly. Besides the *digital twin* relationship between the physical object and the digital object, the physical object and relevant data are connected by various kinds of equipped sensors. The data can also be used for the realization of the digital object in the cloud (servers). The element *service*, which can be considered as various application scenarios, relies on the physical object and digital object and simultaneously its feedback contributes to the improvement of the physical and digital objects. Furthermore, considering the time scale, the interactions exist in different phases of the objects, no matter in the real space or virtual space. There is no doubt that the virtual object, relevant information, connections and services are all convergent to the physical object in the real space.

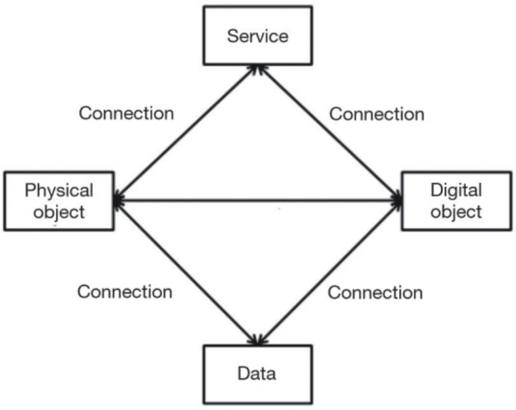


Figure 1. Five elements of the digital twin

– *Self-evolution*

The aim of building the digital twin is the self-evolution or self-adaptation of the physical object, *i. e*., the digital twin could not only reflect the geometry and the concerned physical phenomena in the virtual space but also offer the information (*e.g.* by prediction using the machine learning algorithm) to update the object data in the real space and to improve the relevant procedures such as design, construction and operation, *etc*. According to the extent of the digital twin's involvement in industrial activities and the difficulty of relevant technology, the characteristic of self-evolution for the digital twin can be divided into several levels, as shown in tab. 1. For the digital twins at Level 1, the principal functions are the monitoring and simulation of the relevant physical objects by using sufficient sensors and the mechanism-model- based codes for simulation. These monitoring data and the simulation results are helpful for the optimization of the 3-D geometry of the physical object in the framework of IoT. Simultaneously, virtual reality (VR) is achieved by relevant technologies. The digital twins at Level 2 have adopted AI technology for the control of physical objects. More useful information has been collected to build the AI models by machine learning algorithms. The operation, diagnosis and prognosis of the physical object behaviors could be opti-

Table 1. Hierarchy of the digital twin's characteristic of self-evolution

Level	Functions	Evolution contents
1	Monitoring and simulation	– Status analysis based on real-time monitoring data and IoT technology – Simulation with mechanism-model based codes – Geometry optimization – Realization of VR
2	Intelligence (learning and prediction)	– Adoption of big data and machine learning algorithm for relevant AI model training; – Diagnosis based on the AI model – Optimization based on AI prediction
3	Supervision and automated operation	– Supervision in different stages within the whole lifecycle – Automated operation and optimization of relevant measures
4	Autonomous management	– Strategy assessment and decision making – Application of the autonomous management and control system

mized further based on the AI models. The digital twins at Level 3 are used for supervision and automated operation of physical objects along their lifecycle. Regardless of normal operation or accident conditions, the digital twins can be used to propose optimization or mitigation measures based on deep AI technologies. The highest level of the digital twin, Level 4, emphasizes the usage of the autonomous management and control system for the physical object. By using such a system, the performance of the physical object can be confirmed, and the degraded or failed conditions can be detected intelligently and keep flexibility and adaptability during these conditions. According to maturity, it can be divided into several phases – semiautonomous, nearly autonomous and fully autonomous. Several frameworks of 4-level digital twins for certain application scenarios have been proposed in the nuclear industry, which has inspired our framework for radioactive waste disposal in this study. The researchers in the Idaho National Laboratory and North Carolina State University have reviewed the uncertainty quantification and software risk analysis for digital twins in a nearly autonomous management and control (NAMAC) system [24] which is used to enhance the defense- in-depth for nuclear installation [25, 26], and put forward a detailed framework for the NAMAC system [27]. Garcia *et al.* [28] have proposed a framework for the realization of autonomous management for nuclear systems. Wood *et al.* [29] have studied the framework of an autonomous control system for small modular reactors in detail.

In summary, the digital twin makes full use of the historical operation data, the real-time monitoring data of sensors, and the physical models for the simulation of multi-physics, multi-scale processes in the virtual space to reflect the whole life-cycle behaviors of the corresponding physical system in the real space. As a result, the digital twin can be considered as a virtual duplicate of a system based on a fusion of its offline and online database, the state-of-the-art machine learning algorithms and the relevant models.

METHODOLOGY

This section will introduce firstly the 7-D capabilities of the digital twin system for management, and then the method of transition from the BIM technology to the digital twin before the introduction of the proposed framework of a digital twin for RWR.

Multidimensionality of the installation model

The created model for the installation (of radioactive waste) can be generated in various dimensions (from 2-D-level to 7-D-level), which depends on the data content required from the installation and the relevant technology used for the data analysis [17]. In the traditional industry, 2-D-level and 3-D-level geometric models are used to assist the construction, operation and daily management of installation, especially for structure visualization. The 4-D-level model refers to the introduction of the time dimension into the 3-D-level model. Models defined in this way can be used for the installation visualization in the form of animation. Furthermore, it is helpful for the relevant activity planning and scheduling optimization of installations. The 5-D-level model refers to the combination of *cost* and the 4-D-level model. Some 6-D-level models only consider the sustainability of the installation, but the 6-D-level model in this work involves both sustainability and safety because of the particularity and risk of radioactive waste. The 6-D-level model can make installation in safe conditions, self-sustainable and energy-efficient. It can reduce the probability of accidents and decrease the energy consumption of the installation in the long run. The 7-D-level model is related to installation management. It includes guidelines and procedures for different kinds of management (*e.g.*, quality management, risk management and knowledge management, *etc.*). It can be used to optimize the management of a relevant installation along its lifecycle from the design stage to decommissioning.

Theoretically, all levels of the model from 2-D to 7-D can be achieved by BIM [30]. But based on the literature, most application paradigms using BIM are in the range of 4-D-level or 5-D-level models [31]. The main difficulty is that 6-D-level and 7-D-level models need real-time monitoring data, which requires strong sensor networks and data processing capabilities. It can only be realized after the IoT, big data and high-performance computing have developed to a certain stage [32]. Until recent years, this problem may be solved effectively with the development of digital twins owing to its advantage in the real-time dynamic interaction between the information space and the physical space. Consequently, the different dimension-level capabilities of installation models (geometric model, BIM and digital twin) can be clearly differentiated as shown in fig. 2. The figure also provides a methodology for the transition from BIM technology to the digital twin.

Transition from BIM technology to the digital twin

Compared with a digital twin, BIM has the following shortcomings: it lacks adequate data, notably the real-time monitoring data of the SSC to build a relevant digital object [33] and it lacks tools for lifecycle predictive analysis. With the development of AI technology, these shortcomings of BIM can be made up by the technology of IoT and big data. It is generally be-

Figure 2. Dimension capabilities for the geometric model, BIM and digital twin
***T* = time, *S* = sustainability & safety, *C* = cost, *M* = management**

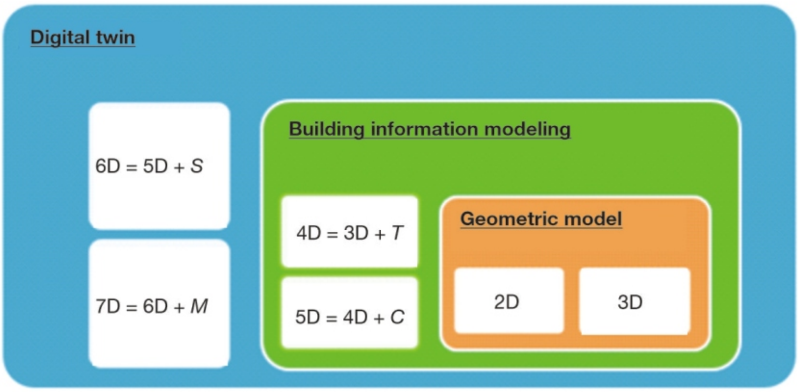
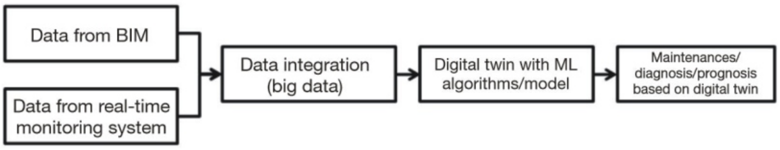


Figure 3. Realization of digital twin based on BIM (the difference between digital twin and BIM)



lieved that the integration of IoT, big data and BIM led to the realization of the Digital Twin. Consequently, the terminology BIM-Based Digital Twin has been invented, which may also reflect the technology development trend. The digital twin of the installation can utilize various sensor networks such as the wireless sensor network, which can be thought of as a part of IoT, to create real-time information and a relevant database of the installation. This dynamic information and database allow for 3-D visualization, real-time analysis and informed decision-making based on the introduction of machine learning algorithms/models. As a summary, the realization of the digital twin based on BIM can be illustrated as shown in fig. 3.

Framework of the digital twin

This framework in this study is based on the AI innovation platform of the company Jinyuyun [34]. This platform was developed to promote the industrial digital transformation and upgrading in the environment of big data and AI. It has been applied in several industrial fields such as power systems, petroleum, natural gas, and transportation, *etc*., covering nearly one hundred industry customers in China [35].

Overall framework

The digital twin involves the integration of several technical layers based on the five elements in fig. 1. Figure 4 presents the overall framework of the digital twin proposed by Jinyuyun. The digital twin framework is divided into two parts: the edge and the cloud. At present, this framework *edge* + *cloud* is very popular in both academic and industrial fields [36].

The edge is the concerned objects of the digital twin, where sensors and devices communicate real-time data to the network (the cloud). From the perspective of an end-user, the edge plays a vital role in the IoT environment. It may be the internal SSC of the installation. But it may also be in the areas where the installation may affect or be affected by, *e.g*., the geological and the hydrological environments of the RWR. The concept of defense-in-depth for RWR involves several barriers (which include engineering and natural barriers). All of these barriers are thought of as the edges for the installation. As a preliminary framework of the digital twin for an RWR, the edges (including the interior and exterior of the installation), are identified in tab. 2. The interior refers to the infrastructures and the internal environment of the repository and they are crucial for the stability and safety of the installation. The exterior is the external environment that

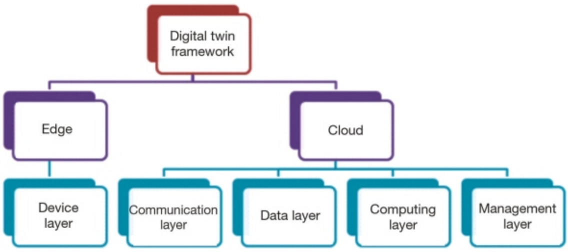


Figure 4. Proposed overall framework of the digital twin

Table 2. Edges of the digital twin for an RWR

Region	Concerns
Interior edge	Entrance, ramps, shafts, tunnel, host rock, foundation beds, tanks, containments, shielding and engineered barriers (clay and concrete), seal components, radioactive liquid collection system, drainage system, and other SSC
Exterior edge	Facility covering, soil, rock, air, groundwater and hydrological environment, vegetation, *etc.*

is involved in the design and operation of RWR. In order to avoid the impact of natural disasters (*e. g.*, landslides and torrents) on the repository which may lead to accidents, the monitoring of relevant exterior edges is also considered in its digital twin.

The cloud of the digital twin is the network and servers that support physical objects and achieve relevant applications. In order to realize the real-time operations and processing, it includes several layers with different functions, *i. e.*, the communication layer for the connection between the edge device and the service, the data layer for the massive data management, the computing layer for the AI training, prediction and modeling, and finally the management layer for status evaluation and decision making. In this mode, the cloud is responsible for completing computing tasks, obtaining the decision results and feeding them back for control.

Device layer

For a digital twin, the edge device is essentially a bridge between the physical object and the digital object. It can be any piece of hardware that is responsible for status monitoring, collecting and filtering data, controlling data flow at the boundary between the edge and the cloud, executing control instructions and completing relevant process management. With the development of IoT, the edge device with intelligence is more and more popular in the management of installations.

The key issues of high level radiactive waste (HLW) disposal are related to the depth of the repository, the stability and waste-isolating functions of the host rock and the engineered barriers, *etc*. [37]. The data of the SSC in the repository, rock stability conditions, rock strength, rock fracturing and fall, clay and soil microstructure, and the environment are acquired by the equipped device for the avoidance of onsite seismicity, flooding, unauthorized intrusion, sabotage and terrorism [38]. In order to obtain all the data required by the data twin of RWR, a variety of sensing and measuring devices/tools with smart intelligence are considered by Jinyuyun at the device layer, *e. g.*, radiation dosimeters, thermocouples, pressure sensors, flow meters, vibration monitors, smart cameras, smartphones, VR glasses, robots and drones, *etc*. Some of these devices have been applied in the domestic projects of energy, transportation, power grid and power facilities.

As an example of intelligent devices, the intelligent inspection robots developed by Jinyuyun can be divided into two types: wheeled robot (the left) and rail-mounted robot (the right), which can be selected according to the site conditions. The intelligent inspection robot can detect the environment of the entrance, ramps, shafts, tunnel, tanks, containments, shielding and engineered barriers, *etc*. of the RWR, and realize the functions of instrumentation panel identification and data acquisition, infrared temperature measurement, radioactive detection, environmental monitoring, security alarm, *etc*.

Communication layer

The digital twin emphasizes edge-to-cloud communication and information exchange for highly efficient management. The communication layer involves an integrated management platform for the relevant edge devices of the digital twin. It has the following functions:

– Registration and account

If a new device is introduced, the concerned device needs to be analyzed and there is a formal registration process. Each service or decision for the digital twin is assigned a universally unique identifier by using the IoT technology, such as radio frequency identification and quick response code.

– Status perception and monitoring

Understanding the operation status of the devices is very important to keep the machine in good operational status. In order to avoid abnormal conditions caused by system faults, the fault occurrence time can be predicted intelligently according to the state estimation algorithm. Once an abnormal condition has been detected during the monitoring process, a warning message will be sent by the communication system, allowing the system administrator to maintain the system before the fault occurs.

– Location perception and positioning

In industry, high-precision positioning is crucial. In the application scenario of RWR, clear positioning is the premise of the safety patrol inspection and measurement. The communication layer includes the position information of all the devices in the digital twin of the repository and responds to the motion of the devices. Sensors and AI methodology have been adopted in order to improve positioning accuracy.

– Display and control

The display and control is used to display necessary information of the digital twin and control the relevant devices or equipment since it directly affects the operation and overall safety of the physical object, *i. e.*, RWR, in this study. In order to improve the effectiveness of display and control, necessary data processing and computation need to be considered before the diversity of display terminals. It should be emphasized that communication protocols provided the means by which vast amounts of information can be transferred throughout different levels of an industrial network while digital twin capabilities enable fascinating process modeling techniques [39]. The following protocols, see tab. 3, are frequently used in the industry. They are familiar to the authors and are recommended for the digital twin of RWR.

Data layer

To achieve the digital twin for a designated industry field, the data analysis is essential work. The characteristics impact the data and information man-

Table 3. Examples of communication protocols suggested in the digital twin of RWR

Protocol	Unit of data transmission	Type of sensor
Micro power wireless network communication protocol	Byte	Wireless temperature sensor
		Wireless humidity sensor
		Wireless vibration sensor
		Wireless micro meteorological sensor
		Wireless gas sensor
		Wireless liquid level sensor
Low-power *ad hoc* network routing protocol	KB	Wireless partial discharge sensor
		Mechanical characteristic sensor
		Vibration sensor

agement strongly and lead to the application of big data technology. The datasets used for big data include different types of data from different sources, such as sensor-measured data, internal variable data, model data, network variables data, operation data, analysis-obtained data, trend data, knowledge data, alarm data and fault log data, *etc*. These datasets comprise a data lake, which is used to support not only steady visualization of the real-time status of physical objects of the digital twin but also their controlling management, upgrade and optimization.

The task for the first step is to identify the crucial parameters which can reflect the status of the RWR. The identification may be based on classical methodologies such as the analytic hierarchy process, fuzzy decision making and expert system, *etc*. The datasets for these parameters consist of three parts of data: the historic measured data, the real-time monitoring data and the simulation results. The historic data refers to the measured data from the situ records during earlier phases and the real-time monitoring data from the installed sensors. The simulation results are from professional codes such as the Monte Carlo transport code and best estimate thermal-hydraulic code *etc*. [40, 41].

Computing layer

The digital twin, as an application simulation-driven R&D innovation, may encounter problems such as difficult inheritance of expert experience, low repetition efficiency and simulation process inconsistency during its development process. In order to reduce repetitive design work and improve efficiency in each stage of the installation of the RWR, the computing layer of the digital twin framework considers an intelligent computing center. It is a full life cycle simulation management platform and service configuration system, which realizes the standardization and automation of the R&D process through the sharing and reuse of intelligent models and role management, so as to quickly respond to and realize the personalized intelligent service requirements put forward by the regulatory agencies or clients. The intelligent computing center involves the following structure and functions.

- *Standardization and automation of the R&D process*: the standardization and the automation of the simulation process are conducive to the mastery of professional software, saving design and research time and ensuring the consistency of results. In addition, it is conducive to the function customization, the integration of different functional codes, the automatic update of the simulation models and data, and the automatic analysis and display of the simulation results.
- *Sharing and repeating of intelligent models*: the intelligent computing center can realize sharing and repeating of intelligent models to build engineering services quickly in the other fields with a lower cost. The developed intelligent computing center of Jinyuyun can transplant its computing services to the RWR digital twin on the premise of considering its radiation and other particularity.
- *Role management of intelligent models*: the rapidly moving digitization strategies may entail deploying advanced administrative practices such as role-based management [42]. The idea of role management is to classify the roles of models based on their application purposes and authorities. It has the characteristics of security, flexibility and strong availability.
- *Knowledge management*: the trend of AI technology is from perceptron to cognition. As an important concern for the digital twin, AI cognition is based on knowledge management, which provides full-stack support from knowledge map modeling, knowledge extraction, knowledge fusion/storage, knowledge computing, knowledge reasoning to knowledge application. In nuclear engineering, the SSC, their attributes and the connection among the SSC is emphasized in the knowledge map.
- *Model/algorithm library*: the intelligent computing center includes cloud servers, which have powerful computing capability and on which the industry engineering codes (such as neutron kinetic codes, shielding calculation codes, and thermodynamic codes, *etc.*) are installed. Additionally, machine learning algorithms including both non-deep learning and deep learning are adopted by the intelligent computing center. Both of them are used for classification, clustering and regression according to the actual needs, shown in fig. 5.

Management layer

As shown in fig. 2, big improvement from BIM to the digital twin is the enhancement of intelligent management, which is reflected in each layer of the digital twin, especially the management layer. The management layer of the digital twin for RWR in-

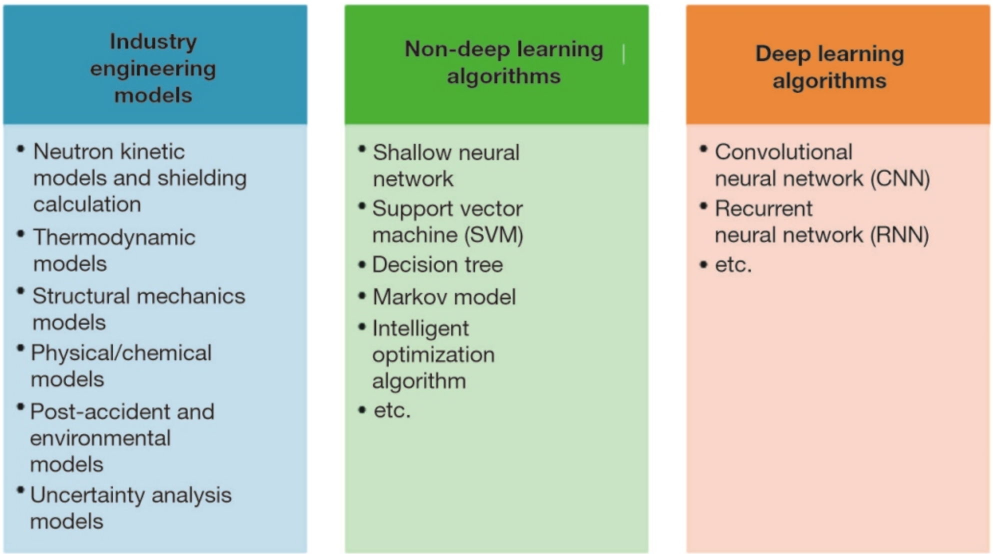


Figure 5. Engineering methods and the machine learning algorithm of the computing layer

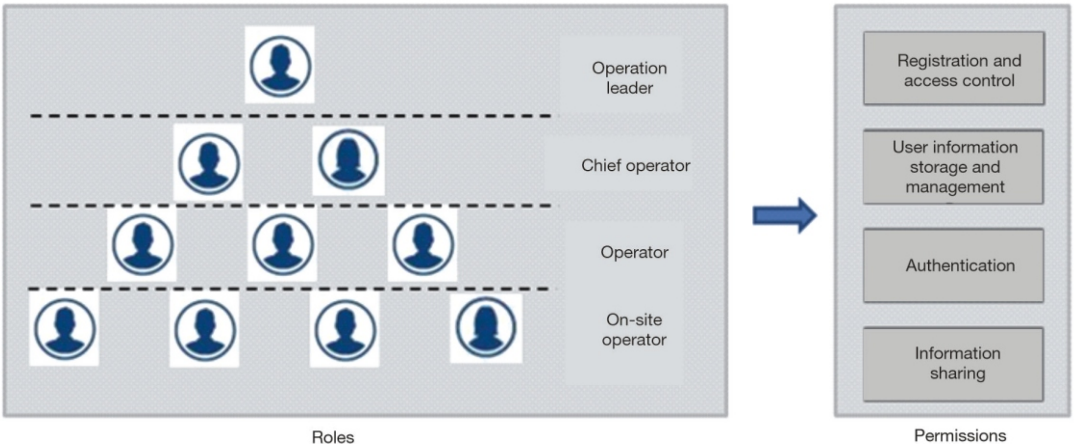


Figure 6. Architecture of user and role management

volves several aspects of content including the management of the system, operation environment, operation monitoring, and application.

– *System management*

The digital twin system management includes the user and role management, process control and relevant resource and device management.

The management of users and their roles is related to the users' memberships in roles, the different rights and permission executions by role members, and the integration of concrete service items in the digital twin environment with the application in the radioactive deposit repository. Consequently, a role-based model is needed for the design of the access control system. Based on the management structure of nuclear engineering installations, the user's role in the digital twin management for the RWR can be divided into 4 types: operation leader, chief operator, operator and on-site operator, as shown in fig. 6. Different users have different permissions such as registration and access control, *etc*.

The process control is characterized by an invasion of the digital control subsystem (DCS) into the digital twin of the radioactive deposit repository. A characteristic feature of the DCS implementation is the great flexibility to make variations in the automation strategy.

The resource and device management involves a database, which includes both the fixed and mobile resources/devices. Combined with the characteristics of the digital twin, the resource and device management are optimized dynamically based on the requirement (*e. g.*, performance and power consumption) by using the methodology of IoT.

– *Operation environment and monitoring management*

Due to the complex operating environment in the RWR, its real-time monitoring and management are cru-

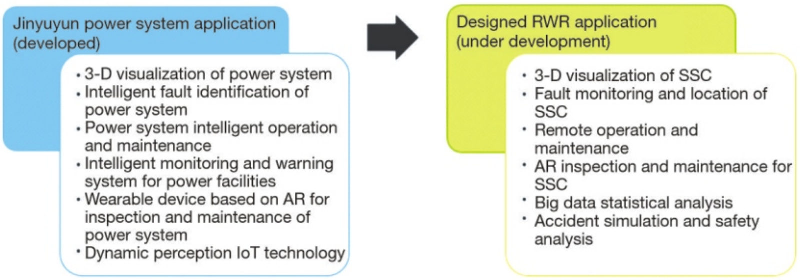


Figure 7. Comparison of applications developed by Jinyuyun in the power system and the applications for RWR which are under development

cial for its operation and safety along with its whole lifespan. Therefore, the influence of the operating environment and monitoring dataset on simulation and prediction is considered in the digital twin system of the RWR.

As a part of the operating environment and monitoring management, the operation environment (*i. e.*, the on-site environment in which the relevant tasks are performed in the RWR) is recreated virtually by the digital twin, which is called the operating environment twin. The configuration of the digital twin can be controlled by the human-computer interaction interface. A real-time view of the environment and configuration is designed for the digital twin system.

The real-time monitoring system for the RWR is an important part of its digital twin system. The requirement of the monitoring system includes versatility, ease of operation, high speed for data acquisition, stability and safety. This is achieved by deep coupling of the device layer, data layer and computing layer with advanced AI algorithms. The monitoring system, which was set at the terminals of devices, uploads the real-time data to the cloud-based data management platform on the servers for data analysis and AI model establishment. This is an iterated process since the analysis results will also impact the design of the monitoring system.

– *Application management*

The application is used to provide services for the installation managers and users. The scope of application development determines the AI level for RWR management. It is so important that some researchers consider it as a separate layer (the top and implementation layer) of DT architecture [43].

Jinyuyun has several applications of AI and IoT technology in the industrial fields. For example, the 3-D visualization system and the wearable device based on augmented reality developed by Jinyuyun have been applied in the management of power systems in several companies in China. These technologies may be applied in the management of the RWR with very few changes, which considered the particularity of the RWR, such as the internal heat source due to the decay heat of radioactive waste, the radioactive environment of the RWR, *etc*. As a summary, fig. 7 has listed the applications developed by Jinyuyun in the power system and the RWR applications which are under development.

APPLICATION

During the planning, construction and operation of RWR, the digital twin of RWR is achieved by the adoption of 3-D visualization tools and using the IoT measurement data and the multi-physical simulation results for analysis. It is based on the Jinyuyun AI innovation platform. The digital twin for the RWR is at the first step of development based on the experience of the digital twin in the other industrial fields. Figure 8 shows the designed interface of the digital twin. Besides the 3-D display of the installation, it involves the project brief introduction, total information of SSC, maintenance information, parameter selection and measurement information. Figure 9 displays the 3-D scene of the instrument room. Around the display screen, crucial information and functions are also shown and used for monitoring, measure execution, and control.

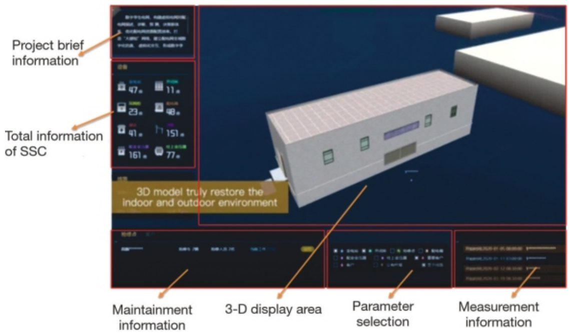


Figure 8. The user interface of the digital twin

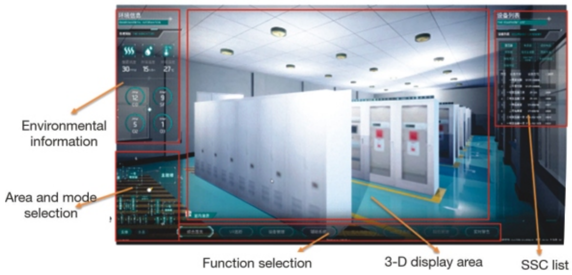


Figure 9. The 3-D display of the instrument room

CONCLUSIONS

This paper has introduced the conceptual design of the digital twin framework for RWR, which has 7-D capabilities for management. It is developed on the basis of the 5-D capabilities of BIM of RWR in the literature and has referred to the latest progress of the digital twin in industry. The framework is based on the experience of the Jinyuyun AI innovation platform, by which a digital twin of the power system has been built and widely applied in China. These successful cases have proved the capability of the digital twin systems to reproduce complicated scenarios with respect to the operation of the RWR. The digital twin system uses the most popular framework *edge + cloud* nowadays with the multi-layer structure of different functions. This framework would be a big step towards the digital twin system of RWR for its whole lifespan management. The first step achievement for the digital twin development of RWR based on the framework is also introduced in the paper.

There are several evident limitations of this study that require deeper research in the near future.

Firstly, this study has only developed the framework of the digital twin for the modeling of RWR. There is huge potential for the detailed structural design and application of digital twin systems to realize its intelligent management during the whole lifespan.

Secondly, the digital twin system is a new concept and still in an initial stage of development, and there's no consensus on its definition for nuclear engineering and the corresponding main features. Therefore, the structure of the digital twin framework needs to be optimized to adapt itself to the special requirements (*e.g.*, the safety requirements) of RWR.

Thirdly, the machine learning methods proposed by this paper for the digital twin system need to be studied in detail to evaluate their adaptability. The evaluation method and standard are also important issues for future research. Furthermore, the optimization of the proposed methods will be another important research issue in the near future.

AUTHORS' CONTRIBUTIONS

The concept and framework were discussed and proposed by H. Xu and T. Tang. The manuscript was written and the figures prepared by H. Xu with the help of Y. Duo. All authors reviewed the manuscript.

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ДИГИТАЛНА ПАРНА СТРУКТУРА ЗА ИЗГРАДЊУ И ФУНКЦИОНИСАЊЕ ОДЛАГАЛИШТА РАДИОАКТИВНОГ ОТПАДА

Дигитални пар сматра се централном компонентом модерне индустрије која је усвојена у многим индустријским областима. Међутим, његова примена у нуклеарном инжењерингу веома је ретка, посебно за одлагалиште радиоактивног отпада што је хитно и проблематично питање. Мотивисани овим захтевом и узимајући у обзир кинеске смернице за истраживање и развој геолошког одлагања радиоактивног отпада високог нивоа (стратегија у три корака до 2050. године за изградњу одлагалишта раиоактивног отпада), предлаже се поступак дигиталног пара за складиштење. Дигитални пар користи оквир "обод + облак" са вишеслојном структуром и може се усвојити у изградњи одлагалишта радиоактивног отпада, значајно ојачати способност управљања, смањити оперативне трошкове, побољшати ниво безбедности и ефикасније се носити са акцидентима. У раду је представљен и први корак за постизање дигиталне парне структуре развоја одлагалишта. Предложена дигитална парна структура одлагалишта радиоактивног отпада у овом раду могла би се широко користити као референца и лако проширити за подршку менаџменту у другим индустријским областима.

Кључне речи: дигитални пар, одлагалиште радиоактивног отпада, вештачка интелигенција, информационо моделовање зграде, студија случаја