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Design, Development and Maintenance of a Digital Twin of vitrification process: a methodological contribution

G. Galand¹, S. Rabah², V. Chapurlat², C. Chabal³, A. Ledoux¹

Abstract: This paper explores the concept of the digital twin introduced by Industry 4.0. Classically considered, a digital twin serves as a virtual replica or a physical asset, enabling various usages such as real-time monitoring, predictive maintenance management, or optimization. The application case is a continuous vitrification process developed in France for the treatment of final nuclear waste here supported by different physical prototypes. Using both normative references and concepts and principles from Model Based Systems and Software Engineering (MBSSE), the contribution introduces a methodological approach for the design, implementation and maintenance of a so-called digital twin system. Through case studies and analysis, the paper intends to demonstrate the potential of this approach in improving vitrification process for nuclear waste.

I. INTRODUCTION

Since the end of 60s, the French nuclear sector guided by French Atomic Energy Commission (CEA) has been developing the nuclear closed fuel cycle. This cycle, as outlined in [1] and [2], serves the dual purpose of efficiency recycling of spent fuel while also identifying final waste. The strategies and methods to manage the used fuels are detailed by [3]. At the end, vitrification process is best suited for industrial applications and long-term packaging. However, vitrification remains more complex, involving thermic, mechanical or even chemical phenomenon. Several types of installations implement this process to test various technologies. In this context, CEA researchers are in charge of testing, comparing, and finally continuously improving vitrification and its various implementations. To this purpose, and considering Industry 4.0 context and digital transformation area, these researchers request to work on as much as possible realistic, relevant and always up to date digital representation of this process as implemented, installed and configured. These requests also aim to consider simultaneously the different viewpoints modelled by other researchers that then describe the vitrification process behaviour with varying degrees of detail and reductionist hypotheses. The goal is indeed to understand and control the entire phenomena that occur during each main steps of vitrification process: calcining, melting, and recycling. In this context, the integration of a virtual representation working as a workbench and a predictive control tools given rise to the concept of the Digital Twin (DT). This innovative concept has gained significant traction across various domains, including manufacturing, transport, construction and energy. DT has been introduced originally to mitigate unpredictable emergent behaviour issues by [4] and is subject today of standards such

as ISO 23247:2021 [5] and ISO/IEC 30173:2023 [6]. By simplification, a DT is a digital representation of a physical asset, also called target entity, to be settle as a digital replica of this target entity i.e. that closely mirrors reality [4]. To this purpose, a DT must implement different target entity's characteristics and particularly functional, behavioural, and physical architectures. It must also take as inputs feedback from various sensors (from physical or logical nature) belonging to the target entity. Then, it must provide processed data as output for target entity control, configuration, prediction or security. Then, considering all these needs and characteristics, the design, development and maintenance of such DT request a lot of efforts, are costly and time consuming.

So, this paper first details the various sources of complexity of the vitrification process and issues involved in modelling and building a DT for a highly sensitive nuclear environment. Second, it introduces an innovative approach based on Model-Based Systems and Software Engineering (MBSSE) [7] to design, develop and maintain any DT of a vitrification process.

II. BACKGROUND

A. The vitrification process

To avoid confusion, we will use the following names to distinguish the process itself, referred to as the vitrification *process*, and the industrial installation that implement it, referred to as the vitrification *prototype*. This prototype is the R&D facility requested by the CEA in order improve the vitrification process. As described by [3], the final waste from a fuel cycle is composed of various chemical elements:

- Fission product: derived either directly from the fission of uranium and plutonium nuclei, or indirectly from the disintegration of radioactive fission fragments.
- Actinides: heavy atoms formed in the reactor by successive neutron captures from the nuclei of uranium isotopes.
- Other elements: result from the degradation of the various components of the spent fuel-processing infrastructures.

This very complex and fluctuating composition of the solutions to vitrify will considerably complicate how the vitrification process is then physically implemented to deal with all the problems caused by the reactions of these different physical-chemical components: redox reactions, corrosion phenomena, highly toxic acid vapours for operators, and among other, radioactivity. [8] and [9] present the original

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different strategies to manage this non-recoverable waste. This paper focuses on the continuous treatment process developed into Orano La Hague plant [3]. Figure 1 illustrates the different phases of the implemented vitrification process. To start, the solution to vitrify enters the process via a mixing and dosing system. Then, pass through the calcination system, which is a resistance furnace that heats the solutions to around 800°C. As a result, the solutions then pass from a liquid phase to a gaseous phase, leaving only the solid products, described above, as ashes: the calcine. The calcinator system finally mix the obtained calcine with glass frit. The melt system implements two main technologies outlined in [3]: Inductive Hot Metallic Melter (IHMM) and Cold Crucible Inductive Melter (CCIM). IHMM heats a metallic recipient by induction to melt the frit with the calcine. Orano Company demonstrated the effectiveness as six units have operated since 1989 in La Hague. CCIM is a recent addition. Its role is to heat still using induction but directly the glass frit, leveraging its conductivity at high temperatures. An internal pressurized water circulation cools the recipient, maintaining an optimal internal glass frit temperature of 1200°C while preventing recipient degradation through temperature regulation. Once the glass frit and calcine mixture has melted, it is poured into a standard vitrification container (CSDV) [3]. The recycling system draws off gases generated during the entire operation, purifying them of toxic elements through multiple cleaning columns. Recovered acids return to the mixing system, while some are used for new fission product solutions. A first issue is then raised, *how to ensure that the modelling of such complex physical system is enough realistic to answer the use cases that will be identified?*

In addition to modelling the physical system, part of the work involves the modelling of the behavior of each process step described by Figure 1. Describing all the physics and interactions involved. Figure 2 describes an initial functional architecture of the vitrification processes, showing the different material flows. It must be then considering the incoming parameters, and outgoing feedback of each main function as an information flow. Last 15 years, several contributions have brought new elements for this modelling. [10] explores the new capabilities of the CCIM and presents the first attempt to couple induction, thermodynamic and fluid mechanic in 3 dimensions for glass melting. [11] describes a new stage of this model with a better understanding of the behavior of melting glass according to the chemical elements inside the solution using a single standard simulation tool: Fluent®.

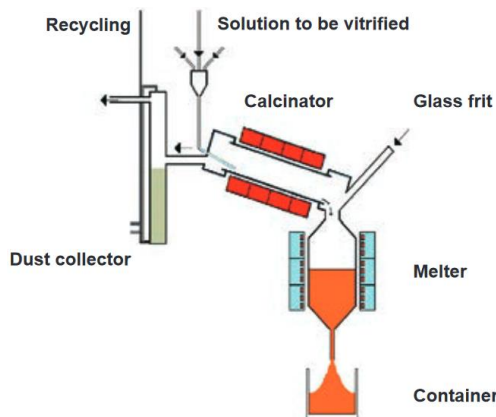


Figure 1: The two-step continuous vitrification process

Finally [12] added the chemical aspect, with kinetic and enthalpy point of view. Each model represents one aspect or point of view of the process. CEA experts in such modelling activities want to detail the entire process behaviour with all interactions between each of the step introduced by Figure 2. Therefore, the next step is to identify what new models are required, and to create a global and realistic model so called *federated model*. The goal of this paper is indeed to introduce the approach to develop this complex federated model, ensuring the interoperability, identifying languages and modelling tools. New issues are then raised: *what are the lacking models? How to identify them? How to federate such different models to build a global and realistic model of the vitrification process?*

CEA conducts R&D activities and tries to improve the vitrification process, developing various vitrification prototypes. Some of them use IHMM initially, and can be reconfigured for CCIM testing. Others prototypes employ different setups like In-Can melter, directly melting fission product and glass frit into the container. Some smaller prototypes implement CCIM for testing and detail behaviour modelling. The large number of prototypes and their complexity make it difficult to monitor all the activities and require a large number of people involved. This increases the risk of losing information and makes knowledge transfer more complex. Nowadays, there is a real lack of solutions to meet this need. R&D activities also mean constant modifications of prototypes to ensure continuous improvement.

The consequence is the crucial need to regularly modify, adapt, and configure the DT. Here come essential issues: *how to ensure the maintainability of the DT? How to help maintainers of the target entity during its exploitation?*

B. Developing of digital solution

1) Standards analysis

Since the concept of the DT emerged in the late 2010s with [4], research has established the foundations of what a DT is. The paper [13] propose a review of technology standards for developing DT. The main introduced characteristic for the DT is the bidirectional and synchronized connection [14] between the DT and its physical asset. Moreover, [15] describes the different proposed architecture and the remaining opened issues in 2022.

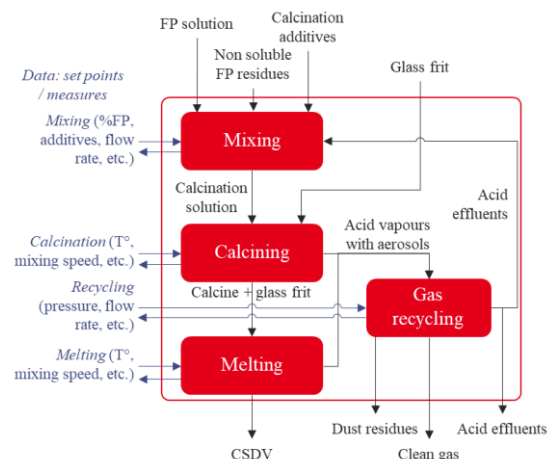


Figure 2: Modelling vitrification process

[16] introduces semi-automatic method to read and implement synoptic model for DT generation. Published in 2021, ISO 23247-1:2021 [5] aimed to formalize the concept of DT in the industrial manufacturing sector, introducing for instance Observable Manufacturing Elements (OME) to represent physical assets, and all functionalities and requirements to perform the association of DT and the OMEs. However, this standard do not fit for all systems. ISO/IEEC 30173:2023 [6] defined then the DT as a digital representation of a *target entity* and proposed *Digital Twin System (DTS)* as the set of digital and physical entities aiming to enable the DT to store and share data, interoperate with the target entity, communicate with the enterprise entities, and interact with users. The goal is indeed to enable convergence between the physical asset and digital states described by the DT at an appropriate rate of synchronisation. Also regarding of operational use cases, [17] propose methodical contribution to define DT application. Despite this important standard contribution, one question remains open: *what standard methodology use to design and implement such DTS ensuring digital representation of a target entity by the DT, bidirectional and synchronized connection?*

2) Industrial vision and practices analysis

From industrial side, digitalisation services providers developed from several years, methods and tools to implement DT for industrial applications, e.g. [18] that promotes to proceed being based on three axis: use case analysis, Technical and Functional Tools, and Data: model. The analysis of use cases to define all specific requirements for the target entities such as the industrial field, project, functional, performance, safety, etc. Technical and Functional tools to build the digital models identified such as BIM software, IoT management and MBSE approach. Finally, promotes *“the construction of data models from the data produced, consumed, and exchanged throughout the project’s lifecycle and adapted to the business objectives”*. [19] and [20] introduce several technical tools and services to build DT such as modelling, simulation, analysis and optimization, even by using virtual reality (VR) tools. DT can be viewed as a closed-loop digital twin [21] to ensure synchronization with the physical entity along its lifecycle. The different actors promotes various design and development tools and environments. Despite this relevant presence of industry in the development of DT, two questions remain: *How is it possible to ensure that these different players use common development methods, definitions and concepts? Furthermore, how can the requested interoperability and federation of the results and models provided by these various tools could be guaranteed within a DTS?*

3) CEA vision and practices analysis

The CEA network, like any other corporate IT network, has several levels of security. A collaborative environment accessible from any certified machine directly on the network, or via authentication on an external network, enables CEA employees to use a wide range of tools and functions. As the data from certain prototypes are sensitive, even confidential, a data security function must be integrated. Following ISO/TR 20123:2023 [22], the challenges to faced are: *“A tricky trade-off between nuclear safety and cybersecurity, which has a very distinct lifecycle: long-life nuclear equipment built to last decades contrast with fast evolution of technologies (e.g. IOT).*

Any changes of process or any technical change can have a huge impact on safety”, the security of every components and data provided by several stakeholders along the whole lifecycle of nuclear systems, and “isolated and protected areas that need interoperability of external systems”. Those security requirements must be considered. The main issues are most technical, *how to ensure the communication between the target entity and the DT respecting all security aspect of CEA IT network?*

C. Discussion

The retained questions will therefore focus on the following issues: 1) *How does the DTS implement the complex and various physical architectures of vitrification prototypes?* 2) *How to integrate all behavioural, representational and more specific models into a unique federated model?*

The contribution introduced in the following is a DTS design, development and maintenance engineering approach crossing DTS definition [6] and MBSSE framework described by [7], the DTS being considered as the System of Interest (SoI) (ISO/IEC/IEEE 15288:2023 [23]).

III. CONTRIBUTION: METHODOLOGICAL APPROACH

The proposed approach is based on the standard ISO/IEC/IEEE 24641:2023 [7], illustrated by Figure 3, where:

- *Plan MBSSE* consists to collect the prerequisites contributing to the effectiveness and efficiency of the approach both within the project and at the enterprise level. It includes defining tasks assignment, the planning, and technical management for setting up the MBSSE approach, as well as resources, knowledge, and knowledge management activities.
- *Perform MBSSE* describes the core System engineering processes, consisting hereafter to model and validate DTS all along its entire lifecycle.
- *Build models* is the set of activities focusing on modeling, verification and validation when performing MBSSE processes. The development of system models includes requirements, functional, physical and behavioral architectures model of the DTS, and the development of discipline-specific models for the vitrification process. Finally, a specific V&V procedure.

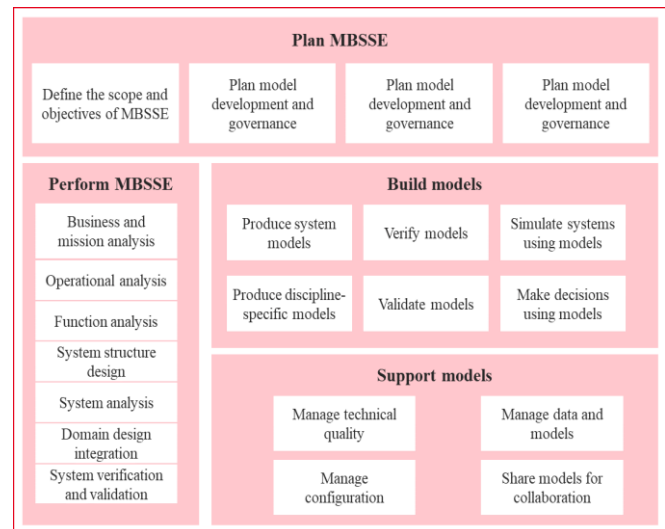


Figure 3: MBSSE process cartography

- Last, *support models* aims to manage data and models exchangeability i.e. ensure interoperability, to assume models technical quality and to manage configurations, the whole allowing to support stakeholders' collaboration.

This paper presents primary results when considering *Perform MBSSE* and *Build models* hereafter applied to vitrification process DTS design and development.

A. Perform MBSSE

The purpose of the SoI is therefore to allow the vitrification of final fuel cycle waste. Its mission will be to implement the continuous vitrification process by connecting the prototype: the target entity, and its digital representation, the DT. The identified issues require an approach that does not focus on solutions here represented by several prototypes developed by the CEA, but rather on functions to use in the SoI to match with any kind of prototype implanting the vitrification process.

As described in ISO/IEC/IEEE 24641:2023 [7] the first step is the context definition of the SoI starting with the lifecycle analysis:

- Development phase: DTS mission analysis, design and technical development including verification and validation activities.
- Exploitation: DTS deployment, operational conduct, and continuous evaluation and adaptation / evolution. During this phase, the DT must conduct iterative updates. It ensures that it remains compliant and interoperable with the target entity after any architecture modification in order to maintain the SoI in operational condition.
- Retirement: overall experience feedback about DTS design and exploitation are then structured and stored for potential future reuse.

For each phase of the lifecycle, operational contexts and stakeholders must be defined. The identification of stakeholders allows structuring and conducting a series of exchanges in the most appropriate format in order to define the global requirements repository and Measures of Effectiveness (MoE) in compliance with ISO 24641:2023 [7]. The operational context led to the complete identification of “*elements within environment external to the SoI and the interactions with those elements*” to enable the DTS to perform its mission inside its operational environment.

In the following, the paper focuses on the exploitation phase. The DTS context contains three other systems put in interaction so called Interfaced Systems: the enterprise entities, the energy supply, and the systems composed of all the DTS users. The Figure 4 shows a model called contextual diagram that put in light these three interfaced systems and the relationships to be achieved in order DTS must fulfil its mission. The stakeholders must then be identified to match with the Users system. Each interact with the SoI to perform specific mission. These interactions will highly influence the requirements. It can be listed for the SoI as those: Research engineers; Technicians, experimental manipulators, and test operators; Facility safety team; IT network management team; DTS development team.

The next step is to describe scenarios arranged in use cases along each considered phase. Use case analysis, as introduced by ISO/IEC/IEEE 15288 [23] and ISO/IEC/IEEE 24641:2023

[7], is widely utilized by system engineers for operational analysis. It focuses on function usage rather than describing the solution or functions themselves. Allowing designer to identify all configuration and to consider all operational scenario along the lifecycle of SoI. This approach matches perfectly with identified issues. As the target entity is not a specific solution but a system implementing the vitrification process. Hereafter illustrated only on exploitation phase, based on ISO 23247:2021 [5], here the list of identified use cases:

- Training: train new operators before going onto the target entity; assist the operator with checklist functions to run the target entity, playback entire tests with post-test data.
- Real-time control: drive prototype, detect any anomaly during running tests, configure the target entity, and access to process components documentation.
- Simulation: simulate the behaviour of the whole or a specific component of the target entity during or outside an experiment.
- Maintenance of target entity: assist the operator during maintenance operations, indicate the degradation of components along the lifecycle, and store anomalies and failures data.
- Maintenance of DTS: the DT must remain consistent with the target entity along the lifecycle, integrate the new model or modify existing model inside the DT federated model, verification and validation (V&V) after an update.

To this purpose, the various operational scenario that describe the expected behaviour of the DTS require “*defining the operational modes, the way of transition between modes and how the system is operated within different modes*”. Each mode authorize different DTS configuration and then to perform one or more of the operational scenarios mentioned above. Using framework such as the OMAG [24], three main types of modes govern DTS operations: operational, faults management and maintenance modes. Operational modes encompass preparation of the mission, the execution, the ending activities of experiments, qualifying tests and operational training. Faults management modes handle various fault levels: minor faults initiate a degraded mode, allowing continued operation albeit with reduced functionality; moderate faults require a brief interruption to restore normal conditions; critical faults trigger a shutdown mode to ensure safety. Maintenance modes ensure the system's operational readiness through preventive and corrective maintenance activities. OMAG promotes then for each mode a set of associated scenarios and configurations.

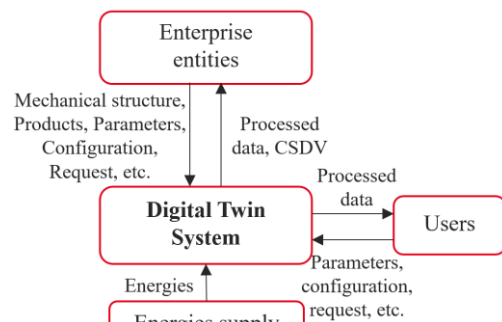


Figure 4: DT system context diagram

In parallel, all these elements allow to complete requirements repository that guides the whole engineering approach, particularly in terms of functions to perform, performance criteria such as Measure of Effectiveness MoE defined by (ISO/IEC/IEEE 24641:2023 [7]), or security and safety imperatives. All these requirements must be respected for all prototypes implementing the vitrification process.

The next step aims to perform functional analysis and a systemic approach to identify and understand the functions of a system. It involves breaking down a system into its functional components and determining how these components interact to achieve the system's overall objectives. The identification of functions must match with the functional requirements identified in the requirements repository. The objective is to identify all levels of decomposition i.e. to structure and arrange the whole set of identified functions and flows (from data, material or energy nature) exchanged between each function. Two techniques can be used:

- Function Analysis System Technic (FAST): to decompose any function at a more precise level;
- Functional Flows Block Diagram (FFBD): to model and structure (e.g. in sequence, in parallel or by using other constructs) both functions and flows.

The final step of design is to build the logical architecture of the DTS. This must reflect the complete allocation of functions into logical components to be identified then structured connected by links and organized in an optimized manner.

As an example, one logical component of the DTS is the DT. Figure 5 proposes a logical architecture regarding ISO/IEC 30173:2023 and ISO 24247:2021.

B. Build models

The ISO/IEC/IEEE 24641:2023 [7] proposes to classify two levels of models: system model and discipline-specific models, by collecting data, then constructing descriptive and analytical models tailored to system aspects. In absence of qualified data and sufficient knowledge, tools like surrogate models or deep learning can be used. Objective: model development and interface creation between system and discipline-specific models. These activities involve proceeds research engineers, ensuring comprehensive system representation.

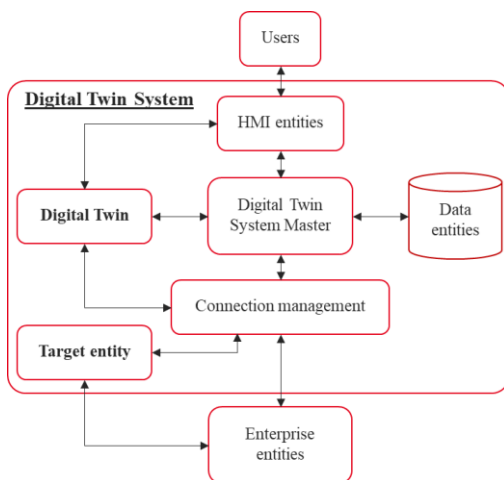


Figure 5: DTS logical architecture

• System models are produced all along the design process described briefly before. They serve as comprehensive representations essential for requirements and design engineering tasks. They capture system features, behaviours, and characteristics, either constructed by domain experts or derived from collected engineering data. Functional, behavioural, temporal, structural, mass, layout, and network models comprise this comprehensive framework, offering a holistic view of the DTS by describing functions, behaviours, timing, elements, mass-related aspects, spatial arrangements, and resource flows among system functions. The modelling activities are guided modelling goals, request selecting appropriate formalisms or languages for representation, and adhering to modelling guidelines and principles introduced by ISO/IEC/IEEE 24641:2023 [7]. The process also entails integrating multiple modelling domains to ensure consistency and coherence across the DTS representation. Particularly, the complete definition of the system models led to the identification of required discipline-specific models.

• The discipline-specific models represent the discipline-specific components of the target entity. Specific engineering constraints and concerns within various disciplines, such as safety, mechanical, thermal, or chemical. Discipline-specific models complement system models by providing detailed insights into domain-specific aspects of the target entity such as calcining, melting, and recycling steps. These models are obviously the most difficult to build, since they depend on knowledge of the associated discipline or the large amount of data available.

Overall, the building of models plays a crucial role in the MBSSE approach by providing a structured framework for creating comprehensive system models and discipline-specific models. These models serve as foundational artefacts for system engineering activities, facilitating requirements analysis, design synthesis, system integration, and verification and validation efforts throughout the system development lifecycle. By adhering to established modelling practices and principles, organizations can effectively leverage the power of model-based approaches to engineer complex systems more efficiently and effectively.

IV. CONCLUSION

The paper introduces the vitrification process for final nuclear waste developed by engineers and researchers at the CEA. The process aims to transform a nuclear waste solution into a standardised glass block for long-term storage. The principal stages of the process are as follows: the solution is calcined to transform it into ash, which is then mixed with glass frit; the mixture is heated to create a bath of molten glass; the molten mixture is poured into a standard container; and the gases produced at each stage are recycled. These different steps, together with the physics and chemical elements involved, make the systems implementing the vitrification process highly complex.

The paper presents the beginning of an operational approach that attempts to facilitate, organize and standardize the design, development and maintenance of the DTS, considered as the SoI, for the vitrification process. The proposed approach introduces two main activities identified in MBSSE standard ISO/IEC/IEEE 24641:2023 [7]. Firstly,

perform MBSSE by realising mission, operational and functional analysis for the SoI, then design the system structure with domain specific design integration, and conclude with the SoI V&V. Throughout this activity, build the models for the DT. First, system models (requirements, functional, behaviour, structure), then discipline-specific models (chemical, thermodynamic, induction, etc...). Finally, ensure complete interoperability to build the unique and complete federated model of the vitrification process.

V. PERSPECTIVES

The major part of the remaining work will consist first to formalize the whole approach into an integrated framework for DTS development. It will secondly consist to complete the definition of functional, logical and physical architecture of the DTS i.e. the resulting DTS to put in exploitation phase. In addition, identify the more technical modelling tools and languages in more detail. Finally, the approach need to cover the entire lifecycle of the target entity, including requirements specific to nuclear industrial facilities, and the end of life of the entire SoI.

The objective is to formalize a complete method for the design, development and maintenance of a DT of vitrification process.

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