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Automation systems and integration — Industrial data — Nuclear digital ecosystem specifications

Systèmes d'automatisation et intégration — Données industrielles — Spécifications de l'écosystème numérique nucléaire

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Foreword

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This document was prepared by Technical Committee ISO/TC *184*, *Automation systems and integration*, Subcommittee SC 04 *Industrial data*.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The purpose of this document is to bring all current knowledge together about standardization of information on nuclear installations in the nuclear industry.

This document provides orientations for how the concept of an industrial digital ecosystem can be realised for the nuclear industry, its installations and practices. These orientations are based on surveys of the state of the art for the adoption of digital methods and technology for the nuclear sectors by the participating members of ISO/TC 184/SC 4 and a review of the current state of the standards for the digital representation of engineering data that are the responsibility of ISO/TC 184/SC 4 and international standards from other TCs/SCs from ISO, IEC, CEN and some de-facto international industry standards.

The objective is to provide the nuclear industry with a common framework to address the intertwined aspects to manage digital information based on standards and related to nuclear facilities and materials.

The nuclear facilities are composed of all the physical structures, systems, and components: mining, fuel manufacturing, nuclear material transport, nuclear power plants (NPPs), reprocessing plants, waste management and disposal facilities.

This document aims to support operational processes in a nuclear ecosystem using digital tools to produce, manage and share information.

It is based on the experience and skills of experts with generic competencies in standards for industrial data, developed during the past years in the edition of standards for product modelling, plant modelling and construction modelling associated with some specific experience of some members in nuclear facilities lifecycle, the corresponding information and records management in the lifecycle.

This document will be updated when new technological advances become available, as many initiatives in the field of the "Industry of the future" are underway, the most relevant of which is the development of the digital twin (DT). The corresponding outcomes can be integrated in a viable roadmap with steps to effectively guide practitioners of the nuclear ecosystem in implementing methodologies and technologies to make effective the benefit of the proposed standards.

This document does not provide answers to all of the issues but does raise questions and identifies barriers for successful implementation which will be addressed to create a digital ecosystem in the nuclear industry. It does provide a simple conceptual framework and a roadmap to guide the actors of the nuclear ecosystem.

To consolidate this perspective, this document has taken into account nuclear technology and the constraints on the nuclear industry. Developing a standardization framework for the nuclear industry could also be useful in order to face long standing issues met in conventional industries regarding information management.

Radioactivity structures all of the activities in the nuclear industry and strongly impacts the needs and the way of modelling facilities and of organising information to support the business processes.

Innovation and standardization will enable a nuclear digital ecosystem (NDE), which could be downsized for conventional industries with specific lighter requirements.

This methodology offers the best guarantee to meet the specific needs of a nuclear ecosystem and to reuse generic models, relationships, and standards already available or prepare their adaptation or extension for the future.

Automation systems and integration — Industrial data — Nuclear digital ecosystem specifications

1 Scope

This document provides:

- a review and summary of the adoption of digital methods and technology in the national nuclear sectors;
- a summary of the state of the art of some of the standards supporting the digital representation and interoperability of industrial data;
- orientation on the use of these standards for model-based systems engineering (MBSE) in order to achieve a nuclear digital ecosystem (NDE);
- a high-level roadmap of the stages by which this ecosystem can be achieved, taking into account the maturity of the actors of the ecosystem, their relationships and the added value of using advanced standards.

NOTE The complete reports from the participating entities are presented in Annexes A to G.

This document includes the following:

- the systems composing the nuclear facilities and their input, output, and other products resulting from interactions in the nuclear system or with its environment;
- the material accounting and the corresponding requirements;
- waste management: all types of nuclear waste produced during processes and activities, and their properties are considered for a seamless management of information in the whole value chain of the nuclear ecosystem.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at https://www.electropedia.org/

3.1.1
asset
item, thing or entity that has potential or actual value to an organization

[SOURCE: ISO/TS 18101:2019]

3.1.2
information
knowledge concerning objects, such as facts, events, things, *processes* (3.1.13), or ideas, including concepts, that within a certain context has a particular meaning

[SOURCE: ISO/IEC 2382:2015, 2121271, modified — Field of application and notes to entry have been removed]

3.1.3
data
reinterpretable representation of *information* (3.1.2) in a formalized manner suitable for communication, interpretation, or processing

[SOURCE: ISO/IEC 2382:2015, 2121272, modified — Notes to entry have been removed]

3.1.4
data element
member of a *data set* (3.1.5)

3.1.5
data set
logically meaningful group of data

[SOURCE: ISO/TS 18101-1:2019]

3.1.6
data quality
degree to which a set of inherent characteristics of data fulfils requirements

Note 1 to entry: Examples of requirements for quality data also include data integrity, data validation, data portability, data synchronization and the data provenance record.

[SOURCE: ISO 8000-2:2022, 3.8.1, modified — Note 1 to entry has been modified.]

3.1.7
digital ecosystem
distributed, adaptive, open, socio-technical system with properties of self-organisation, scalability and sustainability inspired from natural ecosystems

[SOURCE: ISO/TS 18101-1:2019]

3.1.8
digital representation
manner in which information is stored for interpretation by a machine

[SOURCE: ASME Y 14.47 – 2019]

3.1.9
domain
field of special knowledge, which can be further subdivided according to requirements to support a higher level of specialized detail

[SOURCE: ISO/TS 18101-1:2019]

3.1.10
information model
formal model of a bounded set of facts, concepts or instructions to meet a specified requirement

Note 1 to entry: In this context, the description of *domain* (3.1.9) entities in a *digital ecosystem* (3.1.7) addressing lifecycle *asset* (3.1.1) management.

[SOURCE: ISO/TS 18101-1:2019]

3.1.11
interoperability
capability of two or more entities to exchange items in accordance with a set of rules and mechanisms implemented by an interface in each entity, order to perform their specific tasks

Note 1 to entry: Examples of entities include devices, equipment, machines, people, processes, applications, computer firmware and application software units, data exchange *systems* (3.1.17) and enterprises.

Note 2 to entry: Examples of items include services information, material in standards, design documents and drawings, improvement projects, energy reduction programs, control activities, *asset* (3.1.1) description and ideas.

Note 3 to entry: In this context, entities provide items to, and accept items from, other entities, and they use the items exchanged in this way to enable them to operate effectively together.

[SOURCE: ISO/TS 18101-1:2019]

3.1.12
nuclear digital ecosystem
NDE
digital ecosystem (3.1.7) specialised for application to nuclear power facilities and related activities

Note 1 to entry: The objective is to provide principles, methodologies and technologies to enable sharing of shared resources across nuclear industry and beyond, and their specialization in each specific domain and discipline.

Note 2 to entry: There is a trend to name these shared resources "Commons"

3.1.13
process, noun
set of interrelated or interacting activities that use inputs to deliver an intended result

[SOURCE: ISO 9000:2015, 3.4.1, modified — Notes to entry have been removed.]

3.1.14
property
named measurable or observable attribute, quality or characteristic of a system

3.1.15
reference data library
RDL
managed collection of reference data

[SOURCE: ISO 15926-1:2004]

3.1.16
requirement
need or expectation that is stated, generally implied or obligatory

[SOURCE: ISO 9000:2015, 3.6.4, modified — Notes to entry have been removed.]

3.1.17
system
combination of interacting elements organized to achieve one or more stated purposes

Note 1 to entry: A system is sometimes considered as a product or as the services it provides.

Note 2 to entry: In practice, the interpretation of its meaning is frequently clarified by the use of an associative noun, e.g. aircraft system. Alternatively, the word "system" is substituted simply by a context-dependent synonym, e.g. aircraft, though this potentially obscures a system principles perspective.

Note 3 to entry: A complete system includes all of the associated equipment, facilities, material, computer programs, firmware, technical documentation, services and personnel required for operations and support to the degree necessary for self-sufficient use in its intended environment.

Note 4 to entry: A system is also interacting with its environment.

3.1.18
system element
member of the combination of elements that constitutes a *system* (3.1.17)

3.2 Abbreviated terms

AI	artificial intelligence
ALARA	as low as reasonably achievable
ANN	artificial neural network
APR	advanced pattern recognition
BIM	building information model (see ISO 16739-1)
BWR	boiling water reactor
CAD	computer aided design
CAE	computer aided engineering
CDE	common data environment
CDF	core damage frequency
CFIHOS	Capital Facilities Information Handover Specification
CM	configuration management
CNS	Convention on Nuclear Safety
DMS	document management system
DT	digital twin
EAM	enterprise asset management
EPC	engineering, procurement and construction
ERP	enterprise resource planning
eSOMS	electronic shift operations management system
ESPN	nuclear pressure equipment (equipement sous pression nucléaire)
FAIR	findable, accessible, interoperable end reusable
HLW	high-level waste
HVAC	heating, ventilation and air conditioning
ISDC	International Structure for Decommissioning Costs (ISDC) of the OECD
IAEA	International Atomic Energy Agency
IFC	industry foundation classes (see ISO 16739-1)
IIoT	industrial internet of things

IVV	integration, verification and validation
K-PIM	knowledge-centric plant information model
LD	linked data
LLW	low-level waste
LOTAR	long term archiving
LTKR	long term knowledge retention
MBSE	model-based systems engineering
MR	micro reactor
NIST	National Institute of Standards and Technology (USA)
NLP	natural language processing
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission (USA)
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
OO	owner and operator
O&M	operations and maintenance
PIM	plant information model
PLM	product lifecycle management plant lifecycle management
PWR	pressurized water reactor
RDF	resource description framework
RDL	reference data library
SMR	small modular reactor
SNF	spent nuclear fuel
SSC	structure system component
SSoT	single source of truth
SW	semantic web
WANO	World Association of Nuclear Operators
WBS	work breakdown structure

4 Overview of the nuclear industry

4.1 Nuclear fuel cycle

The nuclear industry can be analysed starting with the fuel cycle,[1] and includes all activities from the uranium mining, fuel fabrication, construction of the nuclear installations, O&M of the nuclear installations, decommissioning, fuel reprocessing, waste management and waste disposal.

Whilst reprocessing of nuclear fuel is possible, with facilities to manage the valuable material and the waste produced during the whole fuel cycle, which prefigures a circular economy, it is currently not regularly practiced in a large fraction of the world's NPP fleet.

An integrated management of the data produced during all the fuel cycle and in all the facilities involved in this cycle will bring a clear added value.

The lack of interoperability of data along this cycle is conservatively estimated from 1 % to 3 % of the cost of investment of all of these facilities.[2] At an international level, this represents tens of billions of Euros. Data interoperability and traceability is moreover a regulatory requirement for the nuclear industry.

With the extended use of digital tools at every step of the cycle, it is of the utmost importance that standards support the interoperability of data which must be accessible for reuse for time spans of more than 100 years.

Sharing a global understanding of the situation of the nuclear industry as a system of systems is key.

Systems engineering combined with MBSE in a digital environment offer the best available framework of a global understanding.

Standards to support interoperability of the nuclear ecosystem are numerous and various and concern plants, products, buildings, material, fuel, waste and the environment. The governance of these standards is managed locally by subject matter experts to support specific needs of the actors.

4.2 Nuclear power plant (NPP) safety leadership and management

Safety is a critical issue in the nuclear industry, and the prime public concern of the 1986 Chernobyl accident and the 2011 Fukushima I accident confirmed the concerns. This is reflected in IAEA CNS [73]:

- New NPPs are to be designed, sited, and constructed, consistent with the objective of preventing accidents in the commissioning and operation and, should an accident occur, mitigating possible releases of radionuclides causing long-term off-site contamination and avoiding early radioactive releases or radioactive releases large enough to require long-term protective measures and actions.
- Comprehensive and systematic safety assessments are to be carried out periodically and regularly for existing installations throughout their lifetime to identify safety improvements that are oriented to meet the above objective. Reasonably practicable or achievable safety improvements are to be implemented in a timely manner.
- National requirements and regulations for addressing this objective throughout the lifetime of NPPs are to consider the relevant IAEA Safety Standards and, as appropriate, other good practices as identified inter alia in the Review Meetings of the CNS.

Safety in this clause focuses on key radiation-related aspects of NPP O&M safety, namely nuclear safety, radiation protection and radioactive waste management. Safety data is essential for safety management.

When considering safety in relation to nuclear facilities there are a number of different domains to be considered (both nuclear industry specific and general) including: nuclear safety supervision according to regulations and operation license documents, change management of safety justification basis for the license extension (e.g. change of safety related SSCs, change of operating limits and conditions). Nuclear safety inspection requires the recording data of NPP operation Limiting Condition for Operation (LCO), periodic test data related to safety, parameters of safety system, the defect reporting data, etc.

Radiation protection: the goal of NPP radiation protection is to ensure that O&M personnel are exposed to doses below the limits, and to maintain the radiation at reasonable and feasible levels, and to protect the public and the environment. The main work of radiation protection includes radiation work management, radiation dose control, radiation pollution control, radioactive material control, radiation monitoring, all of which require Radiation Work Permit (RWP) data, ALARA, radiographic testing permit, individual dose record, personnel RP (radiation protection) certificate, etc.

Radioactive waste management: The principles of radioactive waste management are radioactive waste minimization and radioactive effluent optimization. Radioactive waste management requires continuous monitoring data of the effluents, the sampling analysis data, etc.

Safety leadership and management requires the involvement and active participation of all parties and benefits from a system engineering approach. The ISO 8000 series is an important standard which helps to improve NPP safety data quality.

IAEA has provided a series of safety standards as well as international cooperation to ensure that high safety performance is attained. All countries with operating NPPs report on the implementation of their obligations under CNS for international peer review. WANO also has programs to help improve safety.

Digital technology has been implemented to help improve NPP safety, as NPP safety management is still largely paper-based. In China, blockchain technology is used for personal exposure data management. In France, a unique collaborative ‘ESPN digital’ platform centralizes safety requirement management for all stakeholders. In the Pallas project in the Netherlands blockchain principles are adopted by means of attaching a digital signature to each digital statement in the project repository [common data environment (CDE)] which defines meta data such as provenance, access rights, confidentiality, and when applicable, the replace chain (history) of each statement (as per ISO/TS 15926-11).

A few data interoperability barriers hinder NPP safety, for example, the lack of an international standard for the safety classification of equipment, as shown in Table 1.

Table 1 — Illustration of the framework for safety management — Source [74]:

<table>
<tr><th colspan="2">Organizations or countries</th><th colspan="4">Safety classification of I&C functions and systems in nuclear plants</th></tr>
<tr><td colspan="6"><i>Main international standards organizations</i></td></tr>
<tr><td colspan="2" rowspan="3">IAEA safety glossary</td><td colspan="3">Items important to safety</td><td rowspan="5">Items not important to safety</td></tr>
<tr><td rowspan="2">Safety systems</td><td colspan="2">Safety-related items</td></tr>
<tr><td colspan="2">Safety features (for DEC)</td></tr>
<tr><td rowspan="2">IAEA SSG-30</td><td>Function</td><td>Safety category 1</td><td>Safety category 2</td><td>Safety category 3</td></tr>
<tr><td>System</td><td>Safety class 1</td><td>Safety class 2</td><td>Safety class 3</td></tr>
<tr><td rowspan="3">EC 61226</td><td></td><td colspan="3">Systems important to safety</td><td>Systems not Important to Safety</td></tr>
<tr><td>I&C function</td><td>Category A</td><td>Category B</td><td>Category C</td><td>Non-categorized</td></tr>
<tr><td>I&C system</td><td>Class 1</td><td>Class 2</td><td>Class 3</td><td>Non-classified</td></tr>
<tr><td colspan="2" rowspan="2">IEEE</td><td colspan="3">Systems important to safety</td><td rowspan="2">Non-safety-related</td></tr>
<tr><td colspan="2">Safety-related</td><td></td></tr>
<tr><td>EUR</td><td>Safety level of functions / I&C systems</td><td>1</td><td>2</td><td>3</td><td>NS
(non-safety)</td></tr>
<tr><td colspan="6"><i>Selected states with nuclear power programs</i></td></tr>
<tr><td colspan="2">Canada</td><td>Category 1</td><td>Category 2</td><td>Category 3</td><td>Category 4</td></tr>
<tr><td colspan="2">China</td><td>F1A</td><td>F1B</td><td>F2</td><td>Non-classified</td></tr>
</table>

Table 1 *(continued)*

Finland		Class 2	Class 3	EYT/ STUK	EYT (Classified non-nuclear)
France		Class 1	Class 2	Class 3	Non-classified
Germany	I&C function	Category 1	Category 2	Category 3	Non-classified
	I&C equipment	E1		E2	
India		IA	IB	IC	NINS
Japan		PS1/MS1	PS2/MS2	PS3/MS3	Non-nuclear safety
Korea		IC-1	IC-2	IC-3	Non-classified
Russia	I&C function	Category A	Category B	Category C	Non-categorized
	I&C system	Class 2		Class 3	Class 4 (Systems not important to safety)
South Africa		Level 1 Direct influence on safety performance	Level 2 Products important to nuclear safety	Level 3 All products of the nuclear installation	Non-safety or availability related
Switzerland		1	2	3	Non-classified
UK		Class 1	Class 2	Class 3	Non-classified
USA		System important to safety			(Not specified)
		Safety related			

4.3 Differences between nuclear industry and other industries

The nuclear industry is a modern industry; the first power plant, Calder Hall, in the United Kingdom, opened on 17 October 1956.

Nuclear energy has great potential, considering the increase of electrical power in the future, to satisfy the needs of the global population with low carbon emissions. Nuclear energy is characterized by its compactness: a 1 000 MWe power plant uses 27 tons of enriched uranium per year when an equivalent thermal power plant uses 1 500 000 tons of fossil fuel per year.

The nuclear industry is a capital-intensive industry, which is sensitive to financial costs. Thus, it is key, during the lifecyle of the power plant and nuclear fuel cycle, to share data of quality, reduce the design, construction and commissioning duration and costs as well as the periods of shut down for maintenance and inspection because of the availability of the required data for the actors.

Fission produces heat by splitting fissile material and producing radioactive elements. When storing and handling fissile material, care is required to respect mass and geometric constraints to avoid unexpected chain reactions. The different types of radiation interact with the environment, components of the NPP, the atmosphere which results in specific issues for the reliability of the equipment in an environment with high levels of radiation.

The nuclear industry is a strictly controlled industry with high requirements on the traceability of the materials and of the activities.

There are some limitations on the ability to share information on nuclear topics, especially when this crosses national boundaries as with export control regulations.

The activities linked to safety classified equipment complies with regulations on the information management.

Otherwise, common principles are shared globally through rules and orientations edited by the IAEA. However, national regulations are often specific and there is a lack of international standardization in some domains, e.g. the classification of nuclear waste.

Some forms of fuel cycles are adopted for the economic operation of NPPs, such as MOX fuels, by reprocessing the spent UOX fuels. The amount of the final disposal of the spent nuclear fuel (SNF) and the high-level waste (HLW) differs among which types of fuel cycles are used. Therefore, financial planning is important for the management of SNF and HLW during the NPP operations.[1)]

In the decommissioning phase, there is large amount of low-level waste (LLW) by dismantling NPPs. The cost structure of decommissioning NPPs is well summarised by the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD).[75] In this document, the scope of decommissioning cost estimates among European countries and the US is described and there are differences for estimation items between countries due to the different regulations of each country.

Beyond these specificities, the nuclear industry has commonalities and shares the following common concerns with other industries:

- The initial safety philosophy was partially inherited from the aerospace and chemical industries.
- The nuclear industry uses complex calculation codes and simulation tools similar to other advanced industries.
- Nuclear engineering has developed tools for 3D representation to support the design activities.
- A NPP has mechanical equipment, heat exchanger, piping, air conditioning and other systems with similarities with equipment involved in other process industries.
- Nuclear engineering has commonalities with other process industries, and uses P&IDs, other functional schemas and data sheets as in the oil and gas industry.
- Buildings and concrete for biological protection are important components of a NPP or a fuel reprocessing plant and civil works have strong interaction with process and corresponding equipment with periodic data exchange between the corresponding teams.
- The work breakdown structure (WBS) into the international structure for decommissioning costs (ISDC) format, as summarised by OECD/NEA can be a guidance document for the decommissioning phase of NPPs.
- As for all other industries, the nuclear industry encourages the opportunities brought by use of new information technologies and to organize its digital transformation.

In summary, the nuclear industry brings together various domains of manufacturing, process plants and construction and has an interest in the corresponding standards for industrial data and their interoperability.

5 Review of national reports

5.1 General

Descriptions of the current state of digitization in the nuclear sectors of China, France, Japan, Republic of Korea, the Netherlands, the United Kingdom (UK), and the United States of America (USA) are presented for information. These examples can be regarded as a sample from the 20 participating members and 8 observing members of ISO/TC 85/SC6 (Nuclear energy, nuclear technologies, and radiological protection — Reactor technology). The complete reports are reproduced in Annexes A to G. The degree of digitization varies across the sample. Each country has a strategy to increase the use of digitization to an extent that varies according to the distribution of requirements between new build, operations and maintenance (O&M), and decommissioning. The use of advanced digital methods and software technology is increasing amongst all members of the sample.

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1) OECD NEA presentation -- TM on FRs and related FC facilities with improved economics characteristics, Vienna, Austria, 11-13 Sep 2013 (iaea.org).

5.2 New build

China also has a national strategy for digital or smart or intelligent nuclear power, has developed digital handover systems for a few NPPs and looks to the use of DT as a key technology (see Annex A).

Nuclear power is the key to peak emissions by 2030 and carbon neutrality by 2060.

Aligning with the national digital transition strategy, new digital infrastructure and diminishing the gap between EPC and OO data are challenges for China.

The French nuclear industry is demanding sustainable solutions to reuse existing knowledge, support advanced engineering methods as model based systems engineering and robust enough to face future needs and other changes (see Annex B). Digital continuity is a major topic internally for each company and also for the ecosystem. Digital management of safety requirements are now centralized. Waste information management systems are being modernized.

Japan has found that knowledge and experience of new build is decreasing and looks to standardisation for designing and constructing safer and more economical plants for the future (see Annex C).

The Netherlands reports on the design phase of the new Pallas high-flux reactor for the production of radio-active isotopes (see Annex D). The achievement has been to create a complete handover system for design conforming to the recommendations in IAEA TECDOC 1919.[41]

The Netherlands is very active in the development of semantic modelling standards, integrating W3C, process and construction standards.

The Netherlands focuses on maintaining and ensuring the integrity and validity of design basis knowledge and information over time. The Republic of Korea and France have found that different contractors are using different standards for different projects and work is in progress in both cases for national strategies for an integrated project management system.

The Republic of Korea has highlighted the lack of an international standard for the safety classification of equipment and the need for a strong, simple and shared conceptual framework to boost the practical implementation of existing standards and develop additional specifications to fulfil specific requirements of the nuclear industry (see Annex E).

The UK is developing a strategy for the digitalization of the national infrastructure that will include NPPs at some point in the future (see Annex F).

The USA is actively researching the viability of DT technology for NPPs with the goal of developing an appropriate regulatory infrastructure. Current DT technology implementation is limited, but progress is being made in the introduction and use of digital models and data analytics in existing NPPs and by incorporating DTs in prototype development of next generation nuclear projects (see Annex G).

5.3 Operations and maintenance (O&M)

The problem identified in countries that have long established plants is that legacy data is either in paper form or in digital systems that are obsolete. The Netherlands and UK have converted some of these records into searchable digital forms but the conversion of legacy data in obsolete digital systems is more complex. The USA is using Natural Language Processing (NLP) for analysing historical plant data and Artificial Neural Networks (ANNs) to classify and automatize the O&M process. The conversion to more modern methods of data representation will be not possible by purely digital methods alone and will be expensive. A USA consortium is working to develop a fully integrated risk-informed, condition-based maintenance capability on an automated platform. Several NPPs in the USA are implementing Advanced Pattern Recognition (APR) software to recognize normal equipment performance then analyse real-time data as compared to the baseline performance. The policy in France is to ensure the sustainability of digital data for the future. A China energy standard (NB) for NPP O&M data requirement is under development based on a research report approved in 2018. Japan requires standardization for efficient work management for O&M within the conditions of ALARA and lower core damage frequency (CDF). This will support efficient and safe operation with information for precise auditing by the regulatory bodies in order to minimize frequent inspections and to increase operation time.

Management of the information needed to support these activities and the reliability of equipment is important.

The Republic of Korea needs the safety classification of equipment to be ensured at the engineering phase and this requires the development of a nuclear reference data library (RDL). The Republic of Korea is developing a smart plant for fully automated operation and an integrated project management information system has been developed as a national effort. All existing USA utilities have transitioned away from a manual document-based system and component health report and operator logs. Electronic operator rounds [Electronic Shift Operations Management System (eSOMS)], electronic work packages and procedures, and condition monitoring databases are in wide use.

5.4 Decommissioning

The Republic of Korea has no experience of decommissioning whereas the Netherlands has decommissioned the Dodewaard Nuclear Power Plant, a small natural circulation boiling water reactor (BWR) of 58 MW.

Japan has a decommissioning plan for several shut down plants and is developing models for the radioactive inventory of the plants' components in the perspective of the waste management. Japan needs a specific decommissioning project for the site of Fukushima where the situation implies the use of innovative means.

Decommissioning is an important activity in the UK as a result of its early adoption of nuclear power. Twenty sites have been listed for decommissioning as a national strategy. Ten Magnox type plants have been shut down and their fuel removed. One of these sites has been chosen for decommissioning as an example to evaluate procedures and costs. Four prototype plants have been closed and three have been removed. The main problem is that the current description and safety status of many of the active decommissioning sites is not known because records have not been updated or they are housed in obsolete systems. These sites are now being re-documented by means of photogrammetry, laser point scanning and the use of augmented reality. The RDL defined in ISO/TS 15926-4 has been adopted to provide a consistent terminology. There is a lack of standardisation between different client organizations, but the building information model (BIM) is being increasingly adopted for information exchange. The strategy for decommissioning of Magnox in the Sellafield site addresses three specific areas: enterprise asset management (EAM), digital engineering capability, digital decommissioning.

The efforts are done based on standards that are delineated for conventional industries. Meanwhile the nuclear industry has different requirements, for example carrying out dismantling tasks, monitoring radiological inventory and accomplishment of regulatory requirements are some of the differences.

In the USA, 39 commercial nuclear power reactors have been shut down and 25 are in the process of decommissioning under plans submitted to the US Nuclear Regulatory Commission (NRC). Digitalization promises to go beyond the traditional O&M applications of data analytics to almost every aspect of reactor lifecycle ranging from design and licensing through fuel storage or decommissioning.

5.5 Summary of national reports

The collected results of these surveys show that all the nations in this sample have national strategies for the digitalization of the nuclear sector but some or more are more advanced in some respects than in others.

Some common problems include legacy data integration and reuse, including information recorded by non-digital methods, harmonization of the designation and classification standards, development of data models for decommissioning and waste management, lack of guidance for using the modern state of standards for digital representation that would be relevant for the nuclear sector.

Common approaches of standardization should support the use of advanced engineering methods such as systems engineering and enable the benefit of new technologies such as DT, integrated 3D models, simulation models, IIOT, and AI to support new ways of working in the different phases of the lifecycle of a nuclear facility in order to be safer and more efficient.

The preservation of existing knowledge and the creation of new knowledge by skilled teams in a digital environment for its efficient use in the business processes is a common overall challenge for the international nuclear industry of the future.

5.6 High level requirements and some generic use cases

This subclause lists generic requirements partially coming from the national surveys to be checked and validated.

The idea is to define the required capabilities to manage all the industrial data generated during the nuclear lifecycle, these data being related to the facilities (e.g. mines, fuel manufacturing, radio element production, power plants, reprocessing plants and its different facilities, interim waste storage, disposal), the fuel and the waste (e.g. solid, gaseous or liquid).

The thread is the fuel cycle and the representation of the properties of the facilities involved in the whole fuel cycle from uranium mining to waste disposal facilities, of the fuel and of the waste, which will be the basis for the requirements and their management.

- Manage configuration and especially the need to trace requirements and conformance to the operating licence throughout the life cycle.
- Support systems engineering processes and the future shift to MBSE.
- Address the needs of the facilities in operation including new requirements and life extension.
- Integrate legacy data and applications.
- Provide a sustainable and flexible information system supporting the tasks of all of the phases of the lifecycle including the dismantling, the waste management of the dismantled parts and other technological and process waste.
- Provide capabilities to share date on equipment at all stages of the nuclear facility lifecycle from design to decommissioning.
- Provide capabilities to track nuclear fuel, by-products and materials from extraction, through manufacturing to operation and eventual reprocessing, recycling, storage and/or disposal.
- Integrate future business needs and future technological capabilities.
- Consider the human capital role, responsibilities and qualification to the planning. Inclusive perspective and skills /qualification of personnel should be considered.

5.7 Business case based on the adoption of industrial data standards

The business case is considered as the cost-benefit analysis of adopting industrial data standards.

Adoption of data standards in the NDE is directly and indirectly of great value by supporting cost efficiency throughout the activities of the facilities' lifecycle and by enabling the evidence of compliance with the regulatory safety requirements.

Generic studies have been made in the past on the lack of interoperability of data. In August 2004, a NIST report estimated this cost 1 % to 2 % of the cost of the cost of construction of US capital facilities. This cost was voluntarily under-estimated. The basis of the study was all types of construction facilities where industrial facilities represented a small total of about 5 % in 2002.

The cost of the lack of interoperability is certainly much higher and the benefit of greater value for a knowledge intensive and controlled industry such as the nuclear industry.

This document is intended to consider the feedback from countries that contribute to delineate the scope, schedule and WBS for planning the implementation of digitization.

The efforts to implement the vision and orientations of this document are hard to be assessed at this stage. Such assessments should be made in the future for the generic use cases defined in 5.6 and complete the corresponding business cases.

Examples of business cases should be demonstrated in the following more specific illustrations.

- Management of formal requirements, at least explicit and un-ambiguous, throughout the lifecycle.
- Optimization of design of facilities due to improvement of data interoperability between process, civil works, HVAC, architectural, structural, mechanical, electrical and instrumentation and control activities and supporting applications to describe the facilities and compute the data for different design purposes, avoiding re-keying of data, human errors, waste of skilled work-hours and delays.
- Sharing with operators the data and knowledge produced in the design phase to feed O&M applications, for example FMECA models to implement advanced maintenance strategies, which will improve overall equipment efficiency.
- Reuse of data produced in the design, construction and operation phases to prepare for dismantling and to improve waste management activities.
- Long term preservation of knowledge and archiving (e.g. LTKR, LOTAR).

Depending on the maturity of the ecosystem, these examples can be subdivided into sub-business cases with identified lines of benefits. For example, formal requirements can avoid the procurement of non-compliant equipment, thus avoiding, e.g. the material and fabrication costs and the scraps, costs of human hours to manage the issues, loss of revenues due to delays in operation.

A comprehensive digital ecosystem needs the adoption of a set of data standards to efficiently fulfil the requirements of the defined use cases.

6 Framework for enterprise interoperability

6.1 General

ISO 11354-1 specifies a framework for enterprise interoperability that establishes dimensions and viewpoints to address interoperability barriers, their potential solutions, and the relationships between them. ISO 11354-1 defines enterprise interoperability as the ability of enterprises and entities within those enterprises to communicate and interact effectively. An entity in the context of this document is something that exists in itself, actually or hypothetically. ISO 11354-1 applies to manufacturing enterprises but can also apply to other kinds of enterprises. It focuses on, but is not restricted to, enterprise (manufacturing or service) interoperability. It is intended for use by stakeholders who are concerned with developing and deploying solutions based on information and communication technology for manufacturing enterprise process interoperability.

ISO 11354-1 helps to structure stakeholder concerns (e.g. business, process, service, data), the barriers relating to enterprise interoperability (e.g. conceptual, technological, organizational) and the approaches to overcome barriers (e.g. integrated, unified, federated), with contents identifying the various kinds of solutions available to enable interoperability. ISO 11354-1 does not specify the specific mechanisms for the exchange of entities (e.g. information objects or physical objects), nor the manner in which interoperability solutions are implemented.

ISO 11354-1 recognizes three categories of interoperability barriers in realizing and maintaining complex systems in a multiple enterprise environment:

- different organizational structures and maturity, e.g. in information and configuration management (CM), including roles and their fulfilment (organizational);

- — different methods, technology and tools (technological/methodological);
- — different naming, meaning and definitions of things (e.g. conceptual, semantics).

These barriers can be considered as significant if the interactions take place on at least one or all of the four areas of interoperability concerns. The interoperability barriers may manifest themselves on various enterprise levels (e.g. data, service, process and business) as shown in Figure 1.

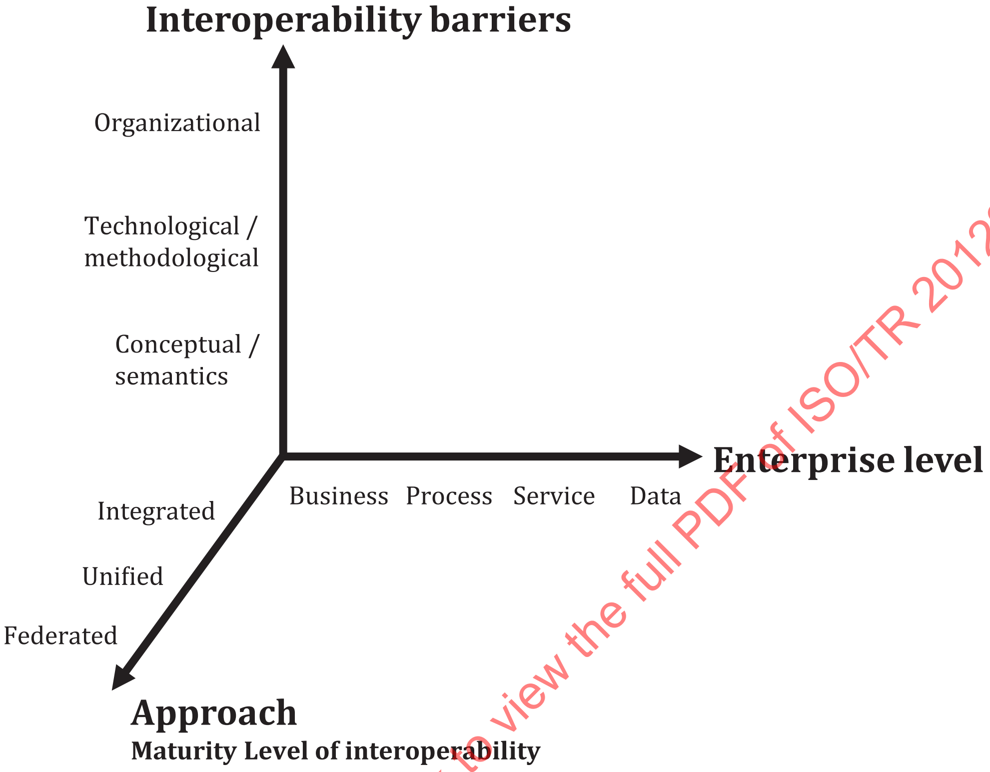


Figure 1 — Interoperability barriers – Enterprise level matrix to position a certain interoperability issue (based on ISO 11354-1)

6.2 Generic barriers to interoperability

6.2.1 General

The following barriers can be recognised in the context of ISO 11354-1.

6.2.2 Organizational

- — No guidelines are available of the required level of engineering and abstract thinking capability of engineers over the lifecycle of a system.
- — Lack of understanding and availability of project characteristics of a system (especially during the system development) in order to enable adequate control of the project-by-project management.
- — Lack of knowledge and understanding on how to interconnect organizations with different maturity levels cooperating in a common project.
- — Lack of recognition of new roles and responsibilities within an organization that is making a shift to a higher position in the supply chain and or is changing from a document centric to data centric way of working.

6.2.3 Methodology and technology

- No integrated, commonly agreed method to guide parties to design, construct and maintain an asset.
- No clear separation of the why, how and what of an organization and the why, how and what of a system, nor is there an ability to integrate all of these aspects.
- No simple to use methodology available to help engineers explain to IT developers of tools what is needed to support their working process.

6.2.4 Semantics

- Lack of guidance in the formulation of abstract and subject things such as objectives, processes and functions
- No common framework for unambiguous communication which can prevent verbal chaos from occurring between various parties involved in projects delivering a complex system.
- Lack of quality of information and data in general and specifically at handover moments in projects.

6.3 Nuclear industry specific barriers to interoperability

There are, however, other specific barriers that affect the establishment of NDE. Some examples are listed below:

- The lack of clear industry wide standards for the data expected at each stage of the lifecycle and the format the data should be provided in.
  - The absence of industry wide data standards is inefficient. Each client currently develops their own bespoke requirements (content and format) to meet their needs. Therefore, suppliers to the nuclear industry need to configure their systems for each client to meet their data needs.
  - A common information standard setting out the information required and data formats for common asset types in the nuclear industry would be helpful to improve efficiency and aid interoperability.
- There is a wide range of guidance and standards that client organisation can adopt. For most clients and suppliers this is a daunting task.
  - There are many competing options for clients to consider. A summary of the key standards and guidance that apply to digital ecosystems would be helpful for suppliers and clients when setting up NDEs. This would need to consider the specific challenges of the nuclear industry.
  - A clear summary of the standards and guidance would allow clients and suppliers to more quickly identify the standards and guidance that exist and identify where there are options to consider.
- There are existing limitations in applying information standards within the nuclear industry due to the distinct characteristics of the industry.
  - Highly specialized equipment for the nuclear industry have distinct requirements for both management practice and information sharing. It is essential to specify these components (e.g. reactor) in order to accommodate various transactions by using global standards. Existing standards of industry-wide (e.g. the ISO 10303 series) or sector-specific (e.g. the ISO 15926 series) perspectives cannot meet these facility-specific (e.g. nuclear facility) requirements.
  - Integration of many different disciplines (e.g. civil, architectural, mechanical, electrical, and so on) is also critical. This fact is supported by the emphasis on the systems engineering for nuclear facilities described in this document. The integration process of the shared information

  depends on the structured set of data, which is practically achieved by using standardized breakdown structures.

  - Sensitivity of some data in the nuclear industry will impact interoperability methods and techniques.

- Some standards that cover data formats for protocols and application security data structures are already available, including ISO/IEC 27034-5 and ISO/IEC TS 27034-5-1 which specifies XML and JSON formats.

6.4 Cybersecurity

6.4.1 General

Cybernuke risks are amongst the most sensitive challenges of all times and are to be taken into account in the exchange of digital information in an NDE.

6.4.2 Main cybersecurity challenges

Nuclear cybersecurity issues are tightly related to nuclear security, with possible direct "physical" impacts on nuclear installations and their facilities. Any threats related to malicious acts, sabotage or terrorism against nuclear industry can have significant economic and public health impacts.

Cybersecurity in nuclear industry is critical and is linked to the following concerns:

- 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. IIOT). Any changes of process or any technical change can have a huge impact on safety.
- Global security of the whole supply chain involving many contractors and sub-contractors to maintain tens of thousands of pieces of a nuclear installation.
- Isolated and protected areas that need interoperability of external systems.

It also implies complex geopolitical dimensions. Major threats are coming from other states. Cyber-attacks are used by some countries to put pressure on others. High level security standards and regulations apply to the nuclear industry, which are widely considered as either operators of vital importance or essential service operators, or both.

Considering these facts, cybersecurity in the nuclear industry involves:

- data integrity and protection against data breach, loss, alteration, and any illegal data transfer;
- sensitive data protection (e.g. employees' data, confidential industrial data);
- protection of industrial equipment (e.g. SCADA, IIOT which significantly increase access points), with high risks such as production shutdown or industrial asset destruction;
- intellectual property rights, industrial espionage.

Nuclear cyber resilience implies:

- a global strategy for the entire supply chain, including technical, technological, organizational, and behavioural aspects;
- raising awareness, anticipating, preventing, detecting, analysing, and responding to cyber incidents and learning from each experience;
- an approach combining "physical" and cyber security.

6.4.3 Main applicable security regulations, norms and standards

The following is a list of the main applicable security regulations, norms, and standards as seen in the French nuclear industry:

- ISO/IEC 27001
- ISA/IEC 62443
- IEC 61508
- NIS2 (Network and Information Systems Security), https://www.consilium.europa.eu/en/press/press-releases/2022/11/28/eu-decides-to-strengthen-cybersecurity-and-resilience-across-the-union-council-adopts-new-legislation/[7]
- PCMNIT (Protection and Control of Nuclear Material Facilities and Transport)[8]
- ISO 19443. Adaptation of ISO 9001 for the nuclear industry organizational security
- INFCIRC/274/Rev1[10]
- National Nuclear Safety Directive [11]
- Cybersecurity Act (2019) [12]
- Data Act (2022) [13]

6.5 Maturity roadmap

To improve interoperability and bridge the gap between the existing paper-document centric way of working in many companies and the target of achieving a data centric and model-based document way of working set out in this document, it is helpful to give guidance and best practices of how to transition towards a data centric way of working from various point of views and maturity stages.

Each stakeholder in the plant engineering supply chain faces different challenges and therefore has a different perspective on the path it needs to follow in a roadmap. The ORCHID project developed a common roadmap that can be tailored based on a framework for companies to progressively build capability to achieve interoperability internally and externally across the engineering supply chain.[14][15][16] The specific goals of the roadmap are to help businesses:

- understand the key principles and business requirements for progressing information standardisation internally and externally,
- assess the information maturity of their business as well as that of industry competitors and partners,
- work individually and with industry partners to improve information management with emphasis on standardisation of information internally and across the engineering supply chain, and
- work with industry standards consortia to assure the required set of standards, tools and services are available in a timely manner.

7 Fundamental pillars of a nuclear digital ecosystem (NDE)

7.1 General

The conceptual framework of the ecosystem should support unified, sustainable information flow from requirements to design, construction, inspection, regulation, operation, maintenance, life extension and decommissioning. It is proposed that the ecosystem should be based on four main pillars: CM, requirements management, breakdown structure, reference data management. These pillars are constituents of model-based system engineering and are described in the following subclauses.

It is worth noting that the IAEA TECDOC-1919,[41] published in 2020, describes an application of plant information models (PIMs) to manage design knowledge through the nuclear plant lifecycle. In its conclusions the report claims that a PIM in form of an engineering data management system is the core for creating an integrated informational foundation for making process-related, engineering and management decisions during plant operation and decommissioning. Data consolidation in a single information storage increases efficiency and ensures transparency and safety of plant operation. The report also identifies some remaining challenges to be addressed in order to implement a knowledge-PIM (K-PIM) framework, including setting the foundation of a common language, intellectual property protection, contractual issues, technical maintenance over the NPP's lifetime or the organizational change of culture to a knowledge-centric paradigm.

This document is a strong contribution for power plants information management based on advanced methodologies and technologies as semantic technologies. It serves as an input for building a common framework for nuclear industry, by defining generic principles, concepts, methodologies, and technologies applicable to all the facilities of the fuel cycle beyond the scope of the design knowledge of nuclear power plants.

7.2 Configuration management (CM)

Configuration management (CM) is a system engineering process for establishing and maintaining consistency of a product's performance and its functional and physical attributes with its requirements, its design and its operational behaviour throughout its life. The achievement of this functionality is ensured by testing. The CM process facilitates orderly management of system information and system changes for such beneficial purposes as to revise capability; improve performance, reliability, or maintainability; extend life; reduce cost; reduce risk and liability; or correct defects. The relatively minimal cost of implementing CM is returned manifold in cost avoidance. The lack of CM, or its ineffectual implementation, can be very expensive and sometimes can have such catastrophic consequences such as failure of equipment or loss of life. The ANSI/NIRMA CM 1.0 [17] gives guidelines for CM of nuclear facilities.

The components of a CM system are illustrated in Figure 2.

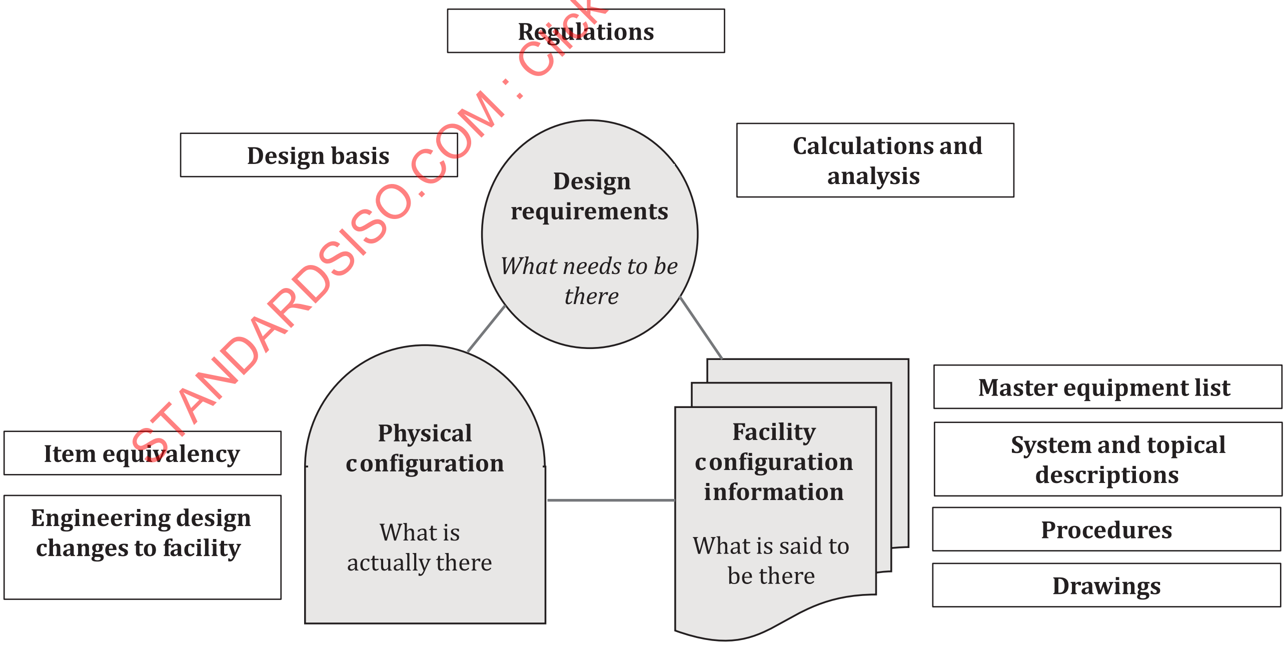


Figure 2 — Configuration management (CM) of a nuclear power plant

NOTE Figure 2 source: IAEA TECDOC-1651.[18]

In ISO/IEC/IEEE 15288 CM is part of the group of technical management processes. ISO/IEC/IEEE 15288 refers to ISO 10007, IEEE Std 828, and EIA-649-B.

EN 9123 does not completely cover the needs of CM required for "one-off "projects.

For the application of information technology to configure NPPs, reference should be made to IAEA-TECDOC-1651[18] and IAEA Safety Reports Series No.65.[19] CM will require a coordinated set of digital representation standards that span the whole range of engineering.

A well-known standard in the context of CM from a document centric point of view is the ISO 15489 series which is about ensuring that adequate records are created, captured and managed in pursuance of legal obligations or in the transaction of business. Record management is the field of management responsible for the efficient and systematic control of the creation, receipt, maintenance, use and disposition of records, including processes for capturing and maintaining evidence of and information about business activities and transactions in the form of records. A record should correctly reflect what was communicated or decided or what action was taken. It should be able to support the needs of the business to which it relates and be used for accountability purposes. As well as the content, the record should contain, or be persistently linked to, or associated with, the metadata necessary to document a transaction as follows:

- The structure of a record, i.e. its format and the relationships between the elements comprising the record, should remain intact.
- The business context in which the record was created, received and used should be apparent in the record and should remain intact.
- The links between documents, held separately but combined to make up a record, should be present.

An important characteristic of the record management process is to ensure the reliability, integrity and usability of the records.

In a data-centric approach, the records management features given above are still valid, however, at the data level.

7.3 Requirements management

A requirement is a capability or constraint to which a project outcome (product or service) should conform. Requirements management is the process of identification, documenting, analysing, tracing, prioritising, and agreeing on requirements and then controlling change and communicating to relevant stakeholders. It is a continuous process throughout a project. It is the basis of systems engineering and connects to the other pillars in the framework. Most of the time, the requirements are specified by using natural language in documents which impedes the computation of the checking of the consistency of a set of requirements and checking the conformance of the design or the equipment to the requirements.

A methodology to manage requirements based on properties has been proposed that offers the following benefits.

- It would enable the automatic checking of the consistency of a set of requirements according to families (e.g. functional, operational, safety) with consistency controlled by set and all together based on IVV processes, allowing for a limit on their number and reduction of the cost in the project.
- It would enable a change in paradigm to be verifying the fulfilment of the requirements by means of simulation, further reducing costs and delays.
- It would enable the automatic checking of the technical specification of equipment for conformity to the requirements.
- The method could bring benefits in commissioning, O&M when the values of a monitored property compared to a requirement can be used to compute the remaining useful life of a component.

A requirement is shared between stakeholders to specify the capability and/or the constraints on an engineered object in conditions that are given. A requirement must be verifiable, so a method of verification must be associated with each requirement. An important assumption is that this is equivalent to expressing the requirement in a formal way as an algebraic expression. In an ultimate digitised industry, computable requirements will be required. However, this will become a challenge for these requirements that cannot just be represented in numbers or standardized qualities.

Lack of standardisation of the representation of the requirement according to ISO/IEC/IEEE 29148 complicates the implementation of systems engineering.

A property-based requirements methodology requires a standardised method for the digital representation of properties. It also requires support of management for developing new skills and training of those responsible for setting requirements.

7.4 Breakdown structure management

A breakdown structure is a system engineering process that enables the separation of a project into smaller components while maintaining their connection to each other and to the system as a whole. An information structure to illustrate breakdown is shown in Figure 3.

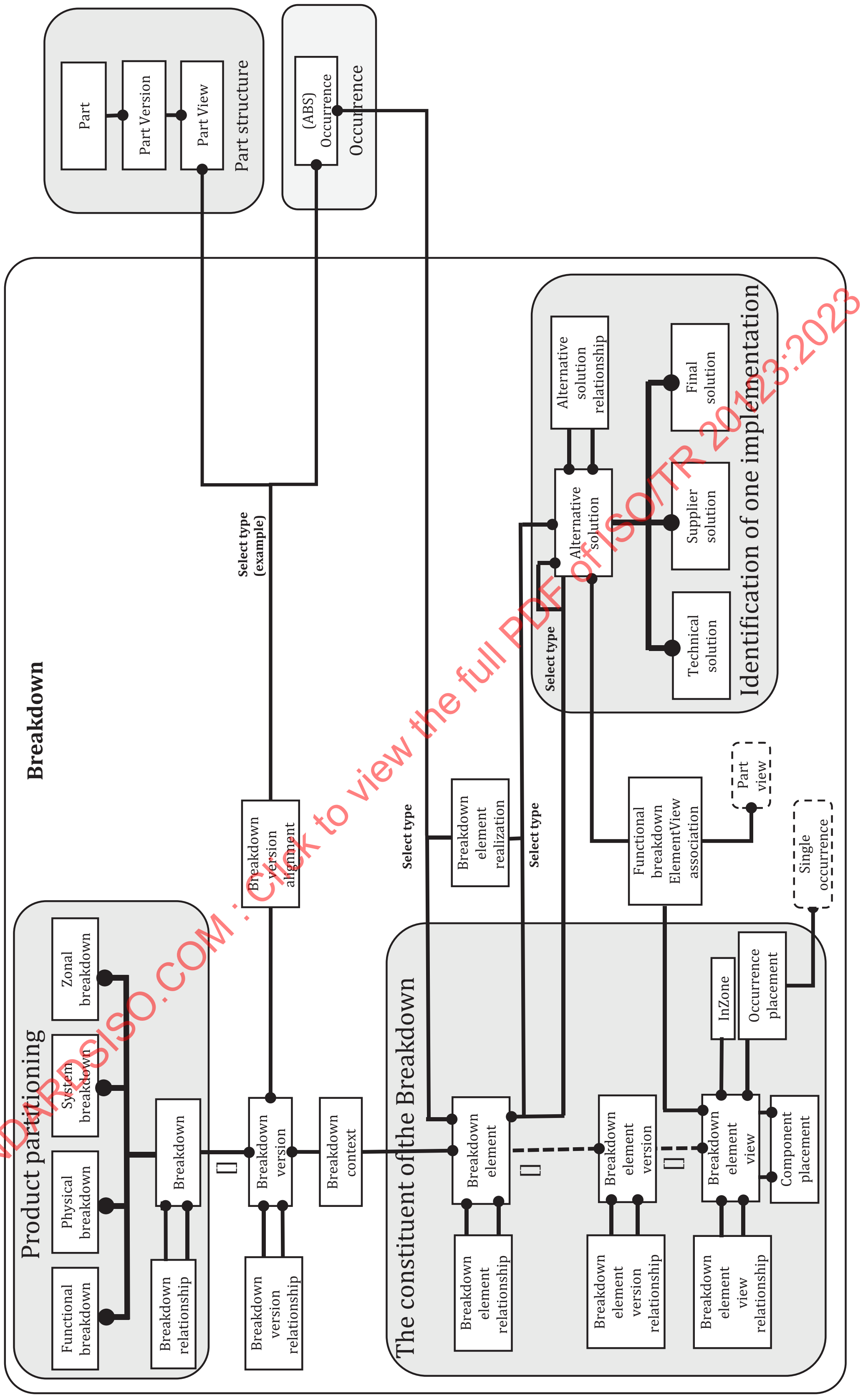


Figure 3 — Information model to illustrate the concept of breakdown

NOTE Figure 3 source: ISO 10303-242:2022, Figure 5 — Simplified overview of the AP242 breakdown BO Model.

A breakdown or aspect view helps to efficiently find the way through a system and to relate relevant, domain or system specific information to the elements of the system of interest. A precondition for making this work is a semantical information network that connects all elements of the breakdowns with each other when applicable.

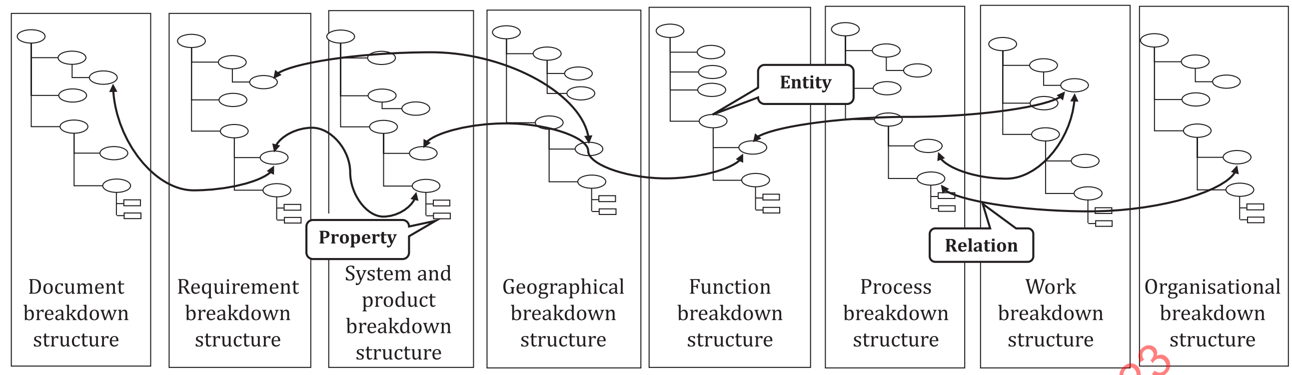
Within a project delivering a complex system such as nuclear facilities, many kinds of subsystems are involved, e.g. the organizational system, the product system. For all of these systems and processes there is a need to structure the composing elements in a particular breakdown structure so that aspect relations can be applied between these elements. In this way a project can be characterized by several breakdown structures, as many as there are interest areas in the project. Trying to catch the whole project in just one breakdown structure leads to a lack of focus on interest and responsibility and inconsistency. If just one project breakdown structure is used, e.g. system elements, system processes and also work packages are often mixed up in the same breakdown structure. Therefore, the approach should be to define as many breakdown structures as there are areas of interest and/or domains. This approach leads to consistent and 'fit for purpose' breakdown structures (as shown in Figure 4). This can also be seen as clouds of information around each decomposition where information elements are interrelated. This will for instance lead to the possibility of finding all system elements, functions, and processes, which are related with a specific work package in the work breakdown decomposition. Some examples of breakdown structures are:

- work breakdown;
- system breakdown;
- functional breakdown;
- geometry (zone)breakdown;
- organization breakdown;
- process breakdown;
- parts breakdown (e.g. group technology, RDL);
- requirements breakdown.

Examples of a set of interconnected breakdown structures are shown in Figure 4.

By focusing on just one interest area per breakdown, the reason to create an element within a breakdown structure can now be based on criteria directly related to the area of interest and will not be influenced by other areas of interest or domains. For example, the breakdown of work packages can be done only from a discipline or domain point of view and the system breakdown can be done from a physical point of view. In this way a clear distinction can be achieved between the product and the process.

The methodology of system engineering gives guidelines on how to structure the design processes, the project stages and the stage results and how they relate to respectively interact with each other. In case of complex projects, the result will be very data intensive, which requires an information system to handle this data in a structured and consistent way.



Key

○ breakdown structure element (instance of an Integrated Information model entity)

⟷ defined association between breakdown structure elements

Figure 4 — Reducing the complexity of a project by breaking down the project into several interrelated project view structures

IEC 81346-1[20] gives the basic rules to build breakdown structures and to designate the objects of a system. IEC 81346-1, [20] IEC 81346-2, [21] ISO 81346-10, [22] and ISO 81346-12 [23] define an information management framework with breakdown structures according to different aspects and to identify the objects building these structures.

7.5 Reference data management

In the context of a digital ecosystem, reference data are data which are validated by subject matter experts, and which can be reused, updated and upgraded by subject matter experts according to governance rules. Reference data can be internal to a company, or to a local ecosystem or at a global level.

The reference data encompass several kinds of data related to material, product, processes and services: requirements, specifications, guidelines, properties, calculation codes, which have been certified by authorities as applicable to nuclear projects. The reference data are traces of knowledge, which are actionable throughout the lifecycle of the nuclear facility, for many use cases such as the following:

- checking the consistency of specific project requirements with more generic requirements applicable to all the projects;
- checking the compliance of suppliers' specification with project and ecosystem's requirements for the procurement of equipment;
- checking the consistency of engineering output, obtained from various design tools each having their own internal libraries;
- simulating the resistance of a structure or the behaviour of a system with qualified computation codes, for instance to support safety studies, and support the test activities;
- supporting trade-offs in design and decision in O&M;
- supporting dismantling activities and waste management.

In an NDE, these reference data will be accessible, reusable, transferable from one application to another application and computable with the other data produced throughout the lifecycle of the facility. The reference data are enriched by the data produced during the lifecycle of the facility, contributing to an update, expansion, upgrade of the initial set of reference data under the control of subject matter experts and data stewards. The compliance of nuclear RDLs with W3C standards should enable their use in the industrial projects.

The reference data including data models can be combined with data driven approaches, using AI algorithms to efficiently improve the reference models and thus the predictions for decision.

8 Model-based systems engineering (MBSE) and standardized industrial models

8.1 Systems engineering and model-based systems engineering (MBSE)

Systems engineering deals, among other aspects, with the development of requirements, their allocation to the items that are being designed and developed when these items are considered as part of a system. The concentration is on the system as a whole, as distinct from the parts considered individually. It requires verification that the design is properly built and integrated and how well the system meets its goals. MBSE is a methodology of systems engineering that focuses on creating and exploiting domain models as the primary means of managing conformance to requirements. The digital thread is a critical capability in MBSE and the foundation for a DT.

A data plan for model-based system engineering is illustrated in Figure 5. Model-based system engineering requires digital models relevant for the nuclear domain that also include the representation of properties.

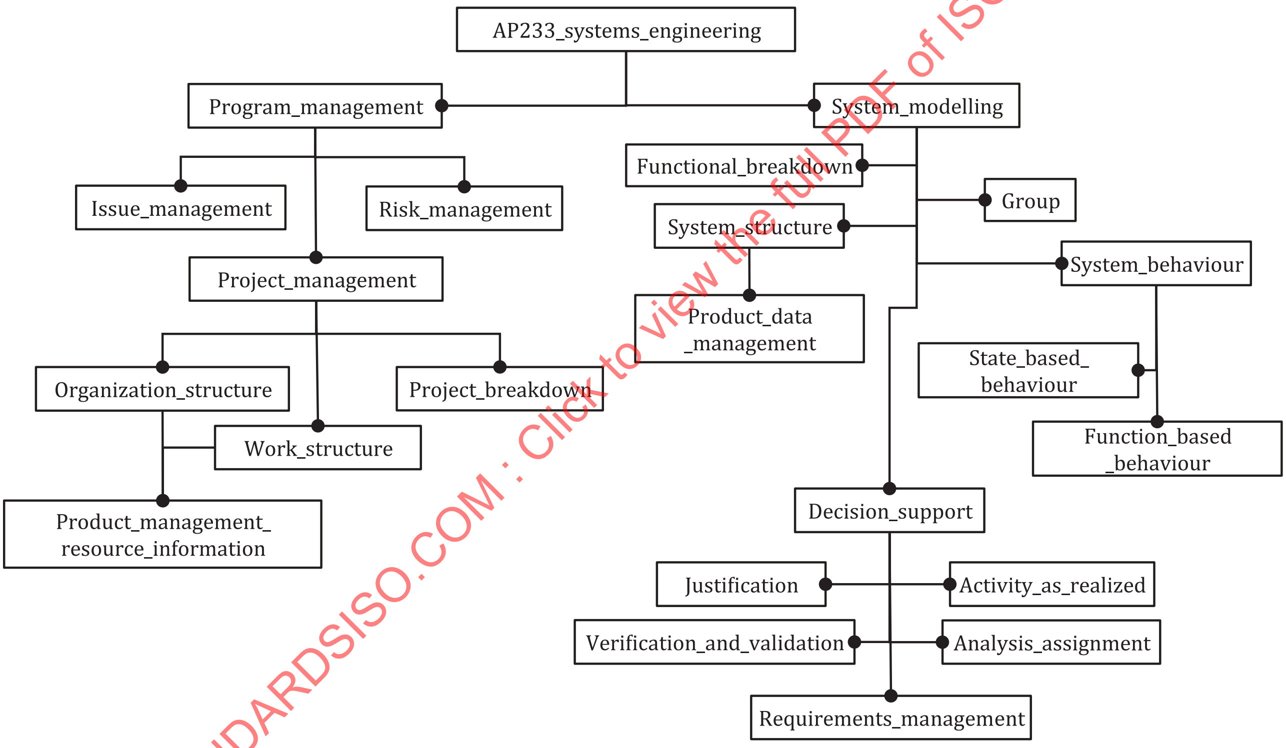


Figure 5 — Data plan for model-based systems engineering (MBSE)

NOTE Figure 5 source: Based on ISO 10303-233:2012, Figure F.2.

An example of how MBSE is differentiated from natural language-based solutions is given in Figure 6. In this figure the following relevant fragments from ISO/IEC/IEEE 15288 are represented by means of semantic modelling.

- Transform the stakeholder requirement-driven view of desired services into a technical view of a required product that can deliver those services.
- Build a representation of a future system that will meet stakeholder requirements and that, as far as constraints permit, does not imply any specific implementation.

- Define the required interactions between the system and its operational environment in terms of interface constraints.
- Define each function that the system is required to perform.

These fragments taken from ISO/IEC/IEEE 15288, can be implemented or interpreted by humans in many different ways (depending on experience and skills) leading to interoperability problems between parties involved in a project if there is no common agreement how to interpret these fragments unambiguously. From these fragments the terms in the blocks of Figure 6 are derived, defined and related to each other in order to capture the information in such an explicit way that one (and ultimately computers) can communicate about the stated four fragments of ISO/IEC/IEEE 15288 in an effective way. This is done by defining entities with a term and definition and relationships between them.

Figure 6 models traceability between on one hand the stakeholder requirements derived from required services ("processes") performed by the system and on the other hand the system requirements that specify implementation free functional physical objects and the interfaces with these functional physical objects. Physical objects interact with their environment, human or other system elements by means of an interface which consist of one or more ports which supports interactions between the system, its environment, and stakeholders (e.g. users) of the system. All interactions that occur during the operational life cycle stage of the system can be modelled using this port principle. Functional objects are realized by means of technical solutions which can result again into functional objects on a lower decomposition level. Technical solutions will have properties which can be used to provide evidence that systems requirements are met.

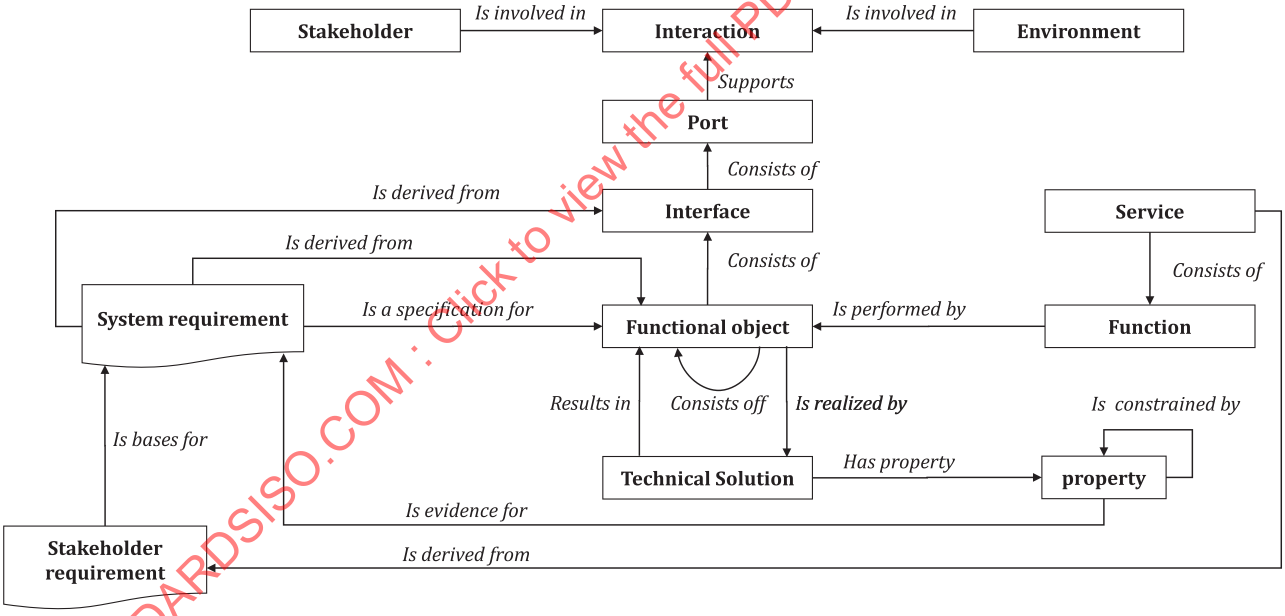


Figure 6 — Information model built upon entities and relationships between them, together representing the essence of the physical design process of a system

This principle can be applied on all 24 models described in the ISO/IEC/IEEE 15288.

8.2 Standardized industrial models

8.2.1 General

ISO 11354-1 identifies three approaches to enterprise interoperability to support MBSE: integrated, unified and federated.

An integrated approach features some common forms which must be implemented in the tools that communicate with each other, i.e. changes or extensions in the vocabulary means a new software version of the tools.

A unified approach features some common meta-model by which software tools can interpret exchanged data unambiguously by respecting the meta data (mostly a shared data model and RDL). Changes and extensions can be done just by changing the agreed model and or library without changing the software of the tools.

A federated approach uses no common forms or meta-model, but dynamic accommodation/adjustment in order to interpret data received from other parties.

In the integrated approach a common form shall be used to represent the exchanged entities ensuring that those entities have a common syntax and semantics and are recognized in the same manner by those enterprises participating in the exchange. This common form shall be sufficiently expressive to capture those details that affect interoperability. The integrated approach is suitable when designing and implementing new enterprise systems. In the unified approach a common meta-level structure applicable for the participating entities shall be identified and detailed. This structure is not an executable entity, unlike the integrated approach that can be directly executable. Instead, it shall provide a means for semantic equivalence to allow mapping between entities. Using this meta-level structure, a translation between the constituent entities is then possible. However, that translation can involve the loss of some information because the participating entities can have different extensions or instantiations of the same meta-level structure.

Three standardised methods have been developed for product data representation in order to support interoperability within and between enterprises:

- The ISO 15926 series;
- The ISO 10303 series;
- ISO 16739-1.

The ISO 15926 series is an example of a unified approach; the collection of standards in the ISO 10303 series is an example of an integrated approach. ISO 16739-1 is an example of a schema that uses the geometry and topology model defined in the ISO 10303 series, but its other constructs are not compatible with the ISO 10303 series.

8.2.2 ISO 15926 series

This document specifies a representation of information associated with the engineering, construction, and operation of process plants. This representation supports the information requirements of the process industry in all phases of a lifecycle of a plant. It aims at the sharing and integration of information amongst all parties involved in the lifecycle of the plant.

The ISO 15926 series is a standard for interoperability and the integration of lifecycle data. The purpose of the ISO 15926 series is to provide a common language for computer systems, thereby integrating the information produced by them.

ISO 15926-1 provides an introduction about how information concerning engineering, construction and operation of facilities is created, used and modified by many different organizations throughout the lifetime of a facility. The purpose of the ISO 15926 series is to facilitate the integration of data to support the lifecycle activities and processes of production facilities as shown in Figure 7.

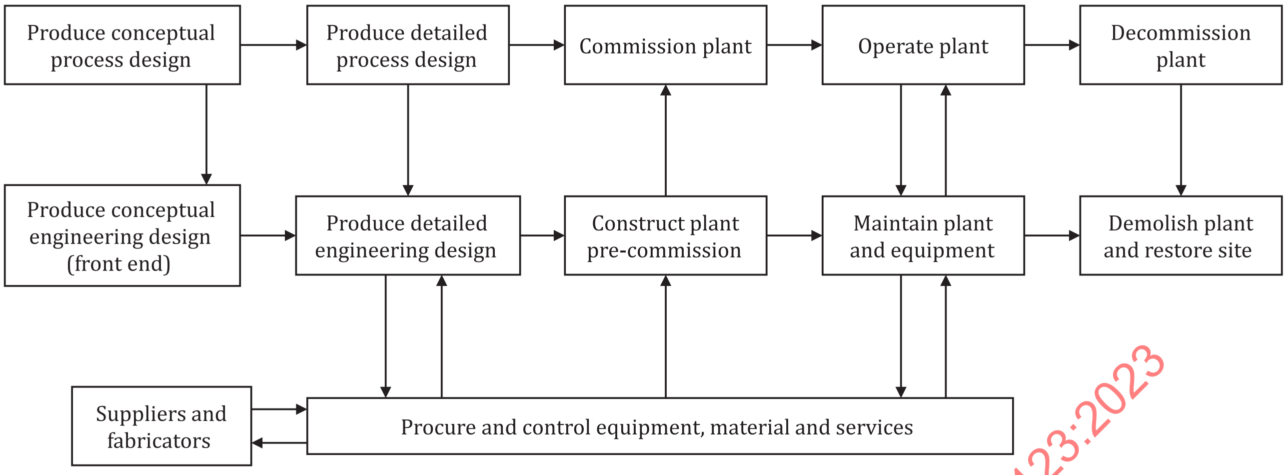


Figure 7 — Activity model of the process plant life-cycle as defined in the ISO 15926 series

NOTE Figure 7 source: ISO 15926-1:2004, Figure 1: Activity model of the process plant life-cycle.

Within the ISO 15926 series, ISO 15926-2 is a core model pertinent to the domain of process plants and oil and gas facilities. ISO/TS 15926-4 provides the explicit RDL and definitions that are used in process industry as reference data provided in a taxonomy of classes. It meets the entities of the data model of ISO 15926-2. The ISO 15926 series approach is designed to support the retention and integration of data through all the phases of a process plant life-cycle from conceptual design, through detailed design, construction, commissioning, hand-over, O&M, to eventual decommissioning and site restoration.

The essence of the ISO 15926 series is to be able to create an explicit and unambiguous data exchange file between two parties that is based on a commonly shared data model (based on ISO 15926-2) and a commonly shared RDL as defined in ISO/TS 15926-4). The software that creates this file makes use of an information model that is derived from ISO 15926-2, which can be seen as a meta-model, and uses references to the RDL to classify all entities contained by the exchange file for encoding the life cycle data of a plant. Input for this can be any life cycle data from a process plant. Software that decodes the exchange file, that can be a different software, also makes use of the same information model and RDL in order to be able to process the received life cycle data in their own information management system as in Figure 8.

An information model that can be executable can be tailored for a project and can be based on three different modelling methodologies i.e.:

a) ISO 15926-7, ISO 15926-8;

b) ISO/TS 15926-11;

c) ISO/TR 15926-14[2], which is used to extend the data model of ISO 15926-2 and the RDL of ISO 15926-4.

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[2] Under development. Stage at the time of publication: ISO/CD TR 15926-14.

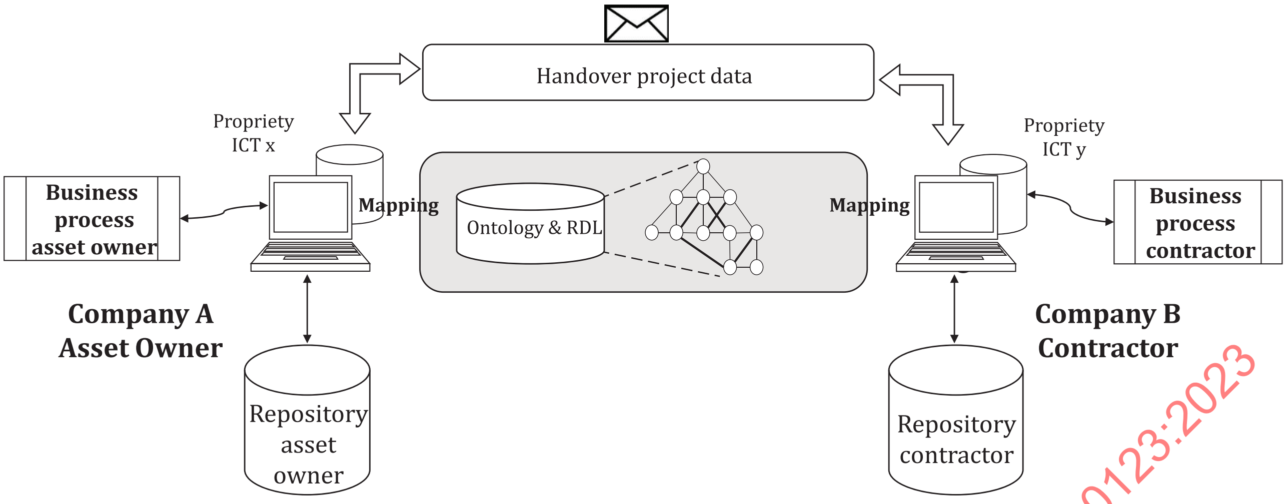


Figure 8 — Data exchange mechanism of the ISO 15926 series based on a reference data library (RDL)

The parts of the ISO 15926 series are like the parts of human speech. When any two people use the same rules of grammar and use the same dictionary, then they can communicate freely. This is the core of the ISO 15926 series.

Specifically, ISO 15926-7 contains what are called templates and is like a phrase book that allows new users to construct a meaningful sentence a bit sooner. ISO 15926-8 provides implementation methods for the integration of distributed systems. It implements the Web Ontology Language (OWL/RDF) and is like the writing media. ISO 15926-9 is like a website or the postal service.

ISO/TS 15926-11 described a semantic modelling approach based on ISO 15926-2 using RDF Schema. Van Ruijven[24] [25] has shown that the ISO 15926 series can be used for a MBSE by means of ISO/TS 15926-11 and was the method used for the handover of the design of the Pallas reactor in Netherlands (see Annex D).

8.2.3 ISO 10303 series

The ISO 10303 series is the initial standard that was developed in 1984 by ISO/TC 184/SC4 for the representation of engineering product data. It was the first International Standard to provide a means for interoperability between different engineering software systems in the same domain and to achieve sustainability for the data by specifying a digital representation that is independent of propriety software.

The principal feature of the ISO 10303 series is a generic model for the digital representation of engineering product data and that is the core resource from which all applications of the ISO 10303 series are developed. Specialisations of the core model are called Application Protocols (AP) and have part numbers in the 200 series, e.g. AP242. Many APs have been developed to meet specific industrial needs and an AP is executable by converting the EXPRESS schema to C^{++} or Java.

Supporting technology has been developed to support the ISO 10303 series and other ISO/TC 184/SC4 standards:

- The EXPRESS language, ISO 10303-11 is an object-oriented computer language for the representation of engineering information.
- EXPRESS-G is a graphical version of EXPRESS to show the structure of a model as a diagram.
- Data file formats that retain the structure of an ISO 10303 model:
  - ISO 10303-21 Plain text presentation;

  - ISO/TS 10303-26 HDF5 Binary presentation;
  - ISO 10303-28 XML presentation.
- Bindings between EXPRESS and computer processing languages – C, C $^{++}$, Java.
- Standardised data access interface (SDAI) to guide interface development.
- Directives for the presentation of documents to supplement the ISO/IEC Directives, Part 2.
- A quality manual to support quality control and quality assurance of the standards.

The ISO 10303 series APs cover a wide range of capabilities for the representation of engineering and manufacturing data and some of these are illustrated in Figure 9. The early stages of the development of the SC4 technology were characterised by each major sector believing that they had a collection of requirements and an identity that were sufficiently different from others that there was a justification to develop an AP for their application. One result was a multiplicity of APs which were very successful for interchanges with systems in the same type of engineering application but were not initially interoperable in some details, although they all used concepts from the generic core model. Experience since then has shown that there is a requirement for more interoperability between the APs within the whole product life cycle. The importance of the change to the extended architecture of the ISO 10303 series is that this interoperability should be easier to develop and to achieve.

The current strategy is to try to reduce the number of APs and to include more capability with each one and to define mappings between them. The development of AP242 as an agreed replacement for the separate APs for the auto and aerospace sectors and the new version of AP209 are examples of this strategy.

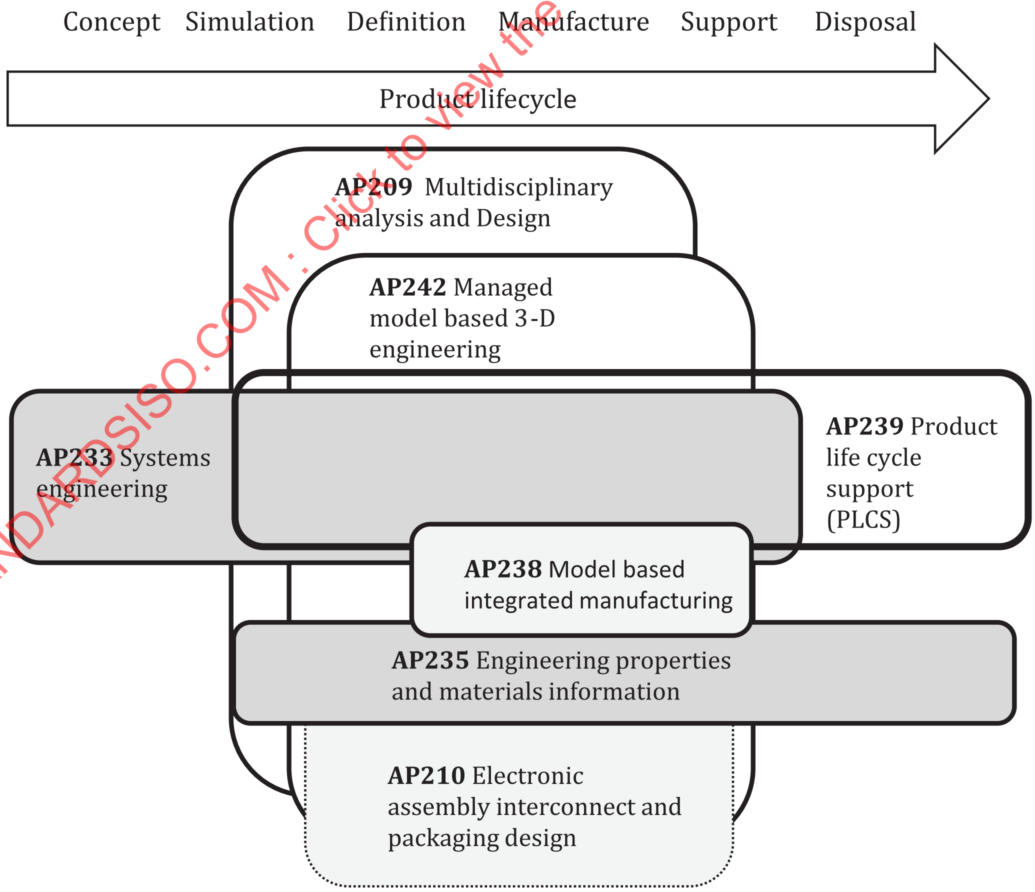


Figure 9 — ISO 10303 standards for model-based engineering

8.2.4 BIM standards for the build environment

8.2.4.1 General

This subclause highlights relevant standards developed in the last decade in the context of the build environment.

8.2.4.2 ISO 16739-1

2013 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries, otherwise known as the BIM, has originally the equivalent status of an ISO 10303 AP in that it consists of an executable schema written in EXPRESS and it is developed for the particular industrial requirements of the construction sector. It uses the geometry and topology model defined in ISO 10303-42 of the ISO 10303 Generic Core Model. CAD software vendors for the construction domain would have had the experience of implementing this aspect of product modelling for applications of ISO 10303-203, ISO 10303-214 and ISO 10303-242. Apart from this example of the ISO 10303 series, the rest of the standard has no relationship with the modelling or the semantics of ISO 10303 APs since it does not use the ISO 10303 series core model as the origin of the semantics. The treatment of materials and properties in particular is completely different from the ISO 10303 series.

However, the basis of ISO 16739-1 which is IFC from the building SMART association develop more and more in its own direction, disconnecting with the ISO 10303 series, and is followed and driven by off-the-shelf 3D CAD modelling software.

The BIM world is evolving quickly with respect to changing from document centric to a data centric way of working. Examples of two relevant BIM standards, e.g. in Europe are EN 17412 and EN 17632.

EN 17412-1 specifies concepts and principles to establish a methodology for specifying level of information need and information deliveries in a consistent way when using BIM. This document specifies the characteristics of different levels used for defining the detail and extent of information required to be exchanged and delivered throughout the life cycle of built assets. It gives guidelines for principles required to specify information needs. The concepts and principles in this document can be applied for a general information exchange and whilst in progress, for a generally agreed way of information exchange between parties in a collaborative work process, as well as for an appointment with specified information delivery. The level of information need provides methods for describing information to be exchanged according to exchange information requirements. The exchange information requirements specify the wanted information exchange. The result of this process is an information delivery. This document is applicable to the whole life cycle of any built asset, including strategic planning, initial design, engineering, development, documentation and construction, day-to-day operation, maintenance, refurbishment, repair and end-of-life.

8.2.4.3 EN 17632

The built environment is the context of EN 17632. In the life cycle of buildings or infrastructure its assets need to be managed across their entire life cycle, involving programming, design, building and operation (as defined by the ISO 19650 series), and the supply chain producing and delivering them. Vast amounts of valuable data about them are created, communicated in a diverse range of formats and data structures and often lost again. In order to manage the assets efficiently and effectively according to the standards practiced in asset management (as defined by the ISO 55000 series), data needs to be findable, accessible, interoperable end reusable (FAIR).

The world wide web consortium (W3C) provides so-called linked data (LD) and semantic web (SW) technologies which can give data common form (syntax) and meaning (semantics), making data FAIR in a vendor neutral fashion.

The aim of this document is to standardize the application of this technology for the built environment in order to enable the data becoming FAIR. This document specifies how the construction and software industries apply this LD and SW technology.

This document addresses syntactic and semantic interoperability for information describing assets going through their life cycle in the built environment. It assumes the underlying technical interoperability provided already by the Internet/World Wide Web (WWW) technology-stack. The syntactic aspects relate to the LD/SW formats and the SPARQL direct access method provided. The semantic aspects relate to the LD/SW-based information models in the form of thesauri and ontologies giving meaning to the information. This document specifies a conceptual Information language with four RDF-based language bindings being SKOS, RDFS, OWL and SHACL. This information language includes a choice of LD/ RDF-based formats and a generic top-level information model ("an upper ontology"). The top-level information model includes a set of generic information modelling patterns for identification, annotation, enumeration datatypes, complex quality/quantity modelling, decomposition, and grouping.

8.2.4.4 ISO 19650 series

The ISO 19650 series is an international process standard for managing information over the whole life cycle of a built asset using BIM. This series can be applied to all types of assets and by all types and sizes of organizations, regardless of the chosen procurement strategy.

The ISO 19650 series provides recommendations for a framework to manage information including exchanging, recording, versioning and organizing for all actors. It is applicable to the whole life cycle of any built asset, including strategic planning, initial design, engineering, development, documentation and construction, day-to-day operation, maintenance, refurbishment, repair and end-of-life. It can be adapted to assets or projects of any scale and complexity, so as not to hamper the flexibility and versatility that characterize the large range of potential procurement strategies and so as to address the cost of implementing this document.

ISO 19650-1 outlines the concepts and principles for information management at a stage of maturity described as BIM according to the ISO 19650 series.

ISO 19650-2 specifies requirements for information management, in the form of a management process, within the context of the delivery phase of assets and the exchanges of information within it, using BIM.

ISO 19650-3 specifies requirements for information management, in the form of a management process, within the context of the operational phase of assets and the exchanges of information within it, using BIM.

Other parts have been published or are currently being developed.

9 Advanced methodologies and technologies for model-based systems engineering (MBSE)

9.1 General

The implantation of MBSE needs further efforts in developing methodologies to manage requirements and share common semantics. These efforts will be supported and benefit from new technologies such as 3D, IIOT, AT, with the implementation of the concept of DT.

9.2 Property modelling

The digital representation of properties is a thread that connects the three pillars of CM, requirements and breakdown structure. The properties of products are described in ISO 10303-233 in the following paragraphs where the concepts are defined in AP233.

A property is a named measurable or observable attribute, quality or characteristic of a systems engineering thing. If it can be measured or observed, it is called a property. Properties have units, values, variances, and probability distributions associated with them. They can be looked up in handbooks of properties of standard materials, they can be calculated from the structure of the thing, or they can be measured directly. In general, they are tensors and can be a function of time. Because of the multiple ways of arriving at a property and its values, it is important to have a reference document that establishes the source of the information.

The International System of Units (SI) provides the most coherent system for expressing property values with units that are used and endorsed internationally. Expressing properties using the SI is recommended. Uncertainties associated with property values may be calculated in accordance with JCGM 100.

A requirement is a statement of a property that a system exhibits. The relationship to system is handled by allocating the requirement to the system that exhibits that property. This formality allows the engineer to consider alternative allocations to different systems that can fulfil the requirement. It is fundamental to trade-off among solutions. Requirements originate from stakeholder needs. As the design proceeds in levels of detail, requirements are derived from other requirements. These "derived from" relationships are preserved as traceability relationships. In a real-world, problem requirements will be changed from time to time. It is critical to trace from a requirement that has changed to other requirements impacted by that change, which on itself is subject of CM.

It is useful to distinguish among three kinds of properties. Structure is the description of how a system decomposes into its parts and how the parts assemble to make the whole. Behaviour is what the system does in response to the things in its environment. This includes both desired responses that satisfy needs, and prevention of undesired responses (failures) that can cause injury, destruction, or loss. Physical property includes all of the measurable or observable attributes, qualities or characteristics of an element that cannot be observed in interaction with the environment. Additional instruments or tools are required to make the measurement or observation. Mass can require a scale for weighing, index of refraction can require use of an optical instrument.

A physical property assigned to part has values. The value can be expressed as a mean, a mean with variance, a probability distribution or a histogram. All of these values are a result of a set of measurements and analysis of the data. The value goes through a series of versions as the system definition evolves. The part is declared to have a required/budgeted value. The part can have a target budget property value as a guide or target as designers consider alternatives. A part, as a whole, can have a calculated property value based on an analysis of the properties, behaviours and interactions of its parts. When a part is built it can have a measured property value.

Other standards such as the ISO 15926 series and ISO/IEC/IEEE 15288 use slightly different definitions of these concepts.

The digital representation of a property of a product in the ISO 10303 series is specified in ISO 10303-45 of the core model that established the principle that the value of a published property depends on the conditions that applied at the time of the measurement, the data environment. Comparisons of property values are only possible when the data environments of the values are the same. Property values represented by ISO 10303-45 can be characterised by their uncertainty and other factors. The core model also includes the means to represent the chemical element composition of the product and its internal structure. ISO 10303-235 extends ISO 10303-45 to include the concept that the meaning (semantics) of a measured property is derived from the measurement method. The specification in ISO 10303-235 provides the resources for the representation of all of the actions and processes that are used to measure a property, including the extension of the processes to derive design values from test values as illustrated in Figure 10. The complete description of the whole sequence of processes enables the origins of a measured property value to be traceable to the source. The property value also can be represented by a mathematical function and by a table, a matrix and by a tensor. An application of ISO 10303-235 to the representation of properties for NPPs has been described by Swindells.[26]

The complete semantics of a property and its value depends on a complex set of relationships that may not be possible to represent completely by an information structure based on ontologies or triple stores such as RDF. The behaviour of a product in a nuclear environment will depend on many influences that may not be possible to reproduce in an external testing procedure.

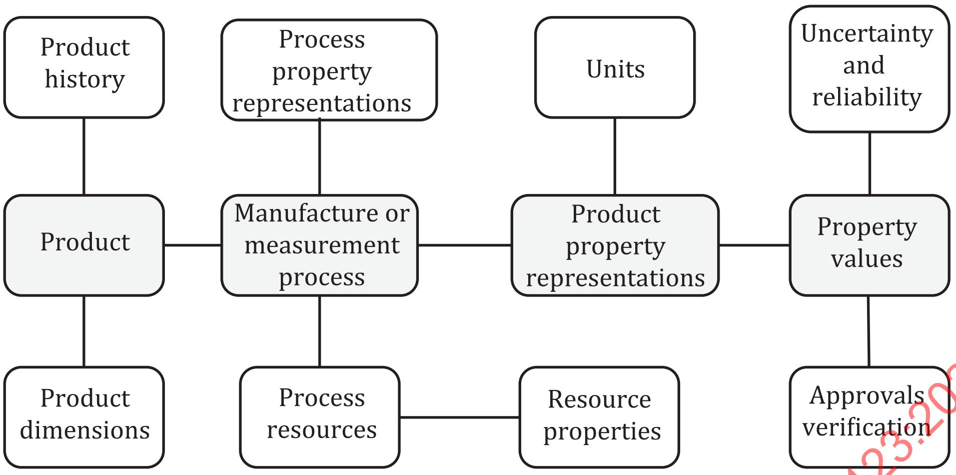
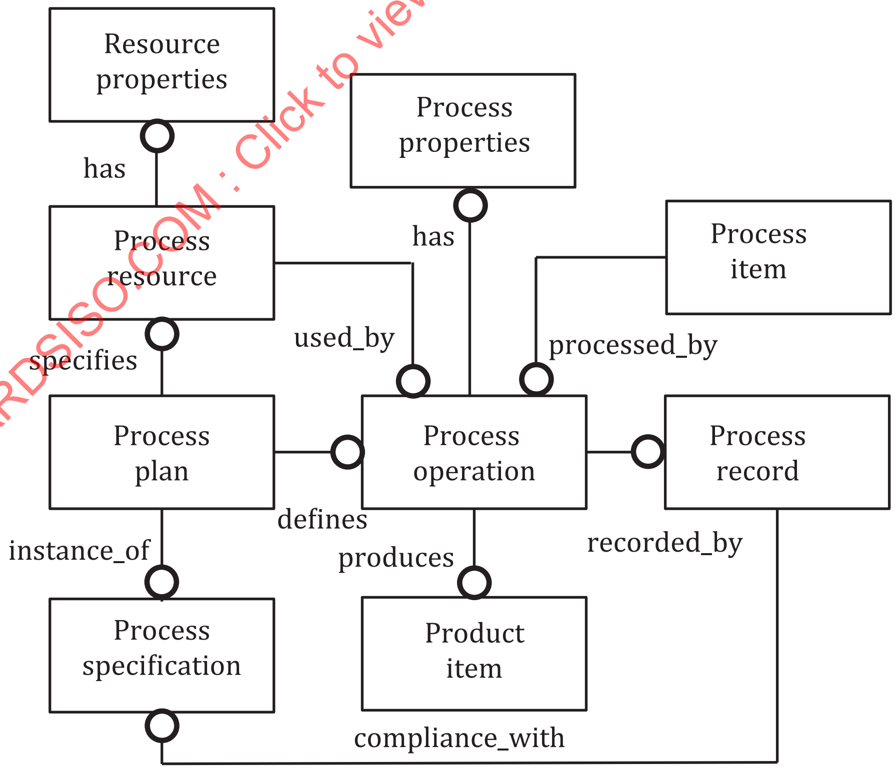


Figure 10 — High-level overview of ISO 10303-235 engineering properties and materials information

9.3 Process modelling

The importance of a process is that processes can be a fundamental influence on the properties of a product and its life cycle. An information model for the specification of any manufacturing process is defined in ISO 10303-49 core model and a high-level view of a model for a process is illustrated in Figure 11. This model is the basis of the description of the stages in the sequence of processes for the measurement of a property in ISO 10303-235. The model can be used for any process, and not only for measurement.



NOTE Based on ISO 10303-235:2019, Figure 2.

Figure 11 — High-level information model for a process

9.4 Semantic modelling of reference data

ISO/TS 15926-4 is an RDL that has been widely adopted as a standard for the terminology used in its domain. It has also been an important feature of the adoption of digital methods in the UK nuclear sector. The experience in Republic of Korea is that the RDL does not include items that are needed for nuclear safety and the RDL does not include some properties that are important for structural integrity. Therefore, for the wider adoption of the RDL as a component of a nuclear handover process further development of the ISO/TS 15926-4 is needed to satisfy the requirements of the nuclear sector.

The ISO 13584 series parts library (PLib) provides an alternative standard for the representation of terminology in a source that can be referenceable from software. PLIB uses an information model, defined in EXPRESS, which is specified in ISO 13584-42 and is common with the information model specified in IEC 61360. The most important consequence of using a standardized information model for a digital dictionary is that other classifications that conform to the same model can be combined. Therefore, concepts and items that are shared between two knowledge domains need only to be defined once in one dictionary and then can be referenced from the classification in the other domain. The capability to reference one classification from a classification in another dictionary conforming to ISO 13584-42 was used successfully in the ISO 13399 series.

The development of ISO 15926-2 and the ISO 13584 series began before the development of the SW. Now, the functions of a dictionary of terms can be achieved with the use of the OWL and the Resource Description Framework (RDF). OWL can be used to define the terms in the EXPRESS schemas of the information models defined in the ISO 10303 series. The ISO 15926 series now uses RDFS/OWL to describe the terminology in the models and the models themselves.

ISO/TS 15926-8 provides rules for implementing the upper ontology specified by ISO 15926-2 and the template methodology specified by ISO/TS 15926-7 into the RDF and OWL languages, including models for reference data specified by ISO/TS 15926-3 and ISO/TS 15926-4, and for metadata. This includes a mapping of the data model from ISO 15926-2 from its EXPRESS format to OWL 2, a methodology for creating an OWL ontology for the reference data in ISO/TS 15926-4 and defines an OWL ontology based on the templates from ISO/TS 15926-7.

9.5 Knowledge representation

The importance of knowledge representation for nuclear installations has been emphasised in the IAEA Technical Document 1919[41] and in the National Survey from Japan (Annex C). Knowledge can have different interpretations but in the context of this document it is taken to be information about the items in a nuclear facility, their history and their relationships to other items in the system. The implication is that this knowledge has to be able to be represented in a digital form that is searchable to extract information that can be transformed into knowledge. The previous clauses have shown how digital information on individual items can be represented. The systems engineering requirement is for the adoption of a method for information about the whole system. One way in which information has been represented is by the RDF that stores item information as a ‘triple store’ in a subject-predicate-object format. These triple stores can be managed in a graph database. Graph databases are designed for depicting relationships (edges) between data points (nodes). Less structurally rigid than relational databases, graph databases allow nodes to have a multitude of edges, i.e. there is no limit to the number of relationships a node can have. Additionally, each edge can have multiple characteristics which define it. There is no formal limit, nor standardization, on how many edges each node can have, nor how many characteristics an edge can have. Graph databases can also contain many different pieces of information that would not necessarily be normally related.

This technology was used for the representation of knowledge for the design of the Pallas reactor (see Annex D).

9.6 Data quality

The concepts of quality assurance and quality control of digital information and data are the same concepts of quality assurance and control as for any engineered product, namely, conformance to a specification in a manner that can be tested. These concepts have been documented in a series of standards in the ISO 8000 series.

Information is defined by ISO 8000-8[27] as knowledge concerning objects, such as facts, events, things, processes or ideas, including concepts, which has particular meaning within a certain context. Data is defined as re-interpretable representation of information in a formalized manner suitable for communication, interpretation or processing. Metadata is data that describes and defines other data. A conceptual model is the model that describes concepts of a universe of discourse. Three types of quality are defined in ISO 8000-8:

— Syntactic quality is the degree to which data conforms to the specified syntax and domain dictionary. For example, a sentence in a natural language meets a requirement for measurable quality if it conforms to the grammatical rules of the language and uses words defined and spelt according to the relevant language dictionary.

— Semantic quality is the degree to which data corresponds to the information that they represent. It is the unique and unambiguous correspondence with the external objects that the data represent. For example, a sentence has to be a true statement. The measurement of this quality requires a match to the requirements of the external objects in the real world as viewed through a conceptual model of this world. In product data technology the conceptual model is the information model for a given engineering requirement that is standardized in the appropriate International Standard.

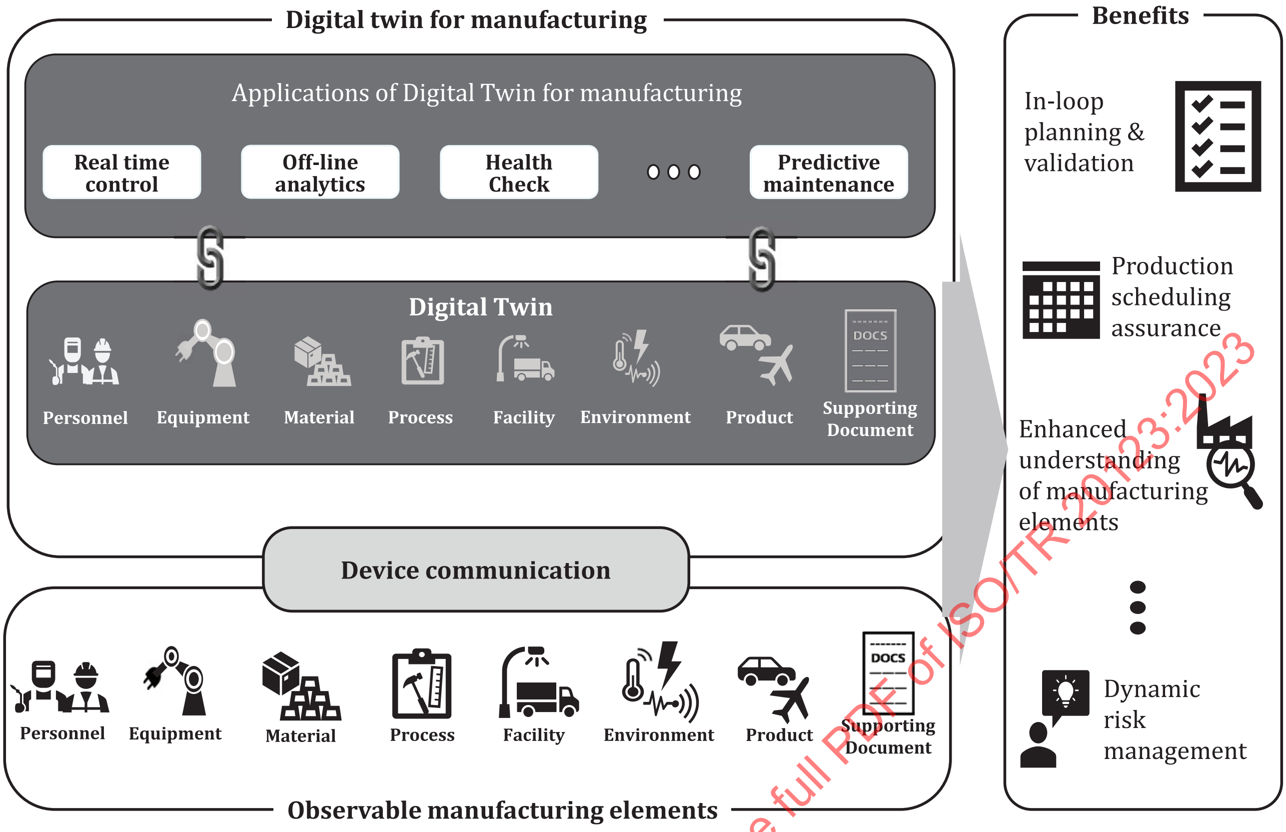
— Pragmatic quality is the degree to which data is suitable and useful to those who use them, i.e. the data must be understandable to the user. In applications of product data technology, the user will be the computer system that is the receiver in a communication and exchange process. The requirements are therefore to know if the computer software application can use the data provided by the data file that it receives and, further, to evaluate whether a software implementation of the product data standard conforms to a complete and accurate image of the conceptual model in the standard.

9.7 3-D geometry and topology

Three-dimensional digital models of the geometry and topology of a product are a fundamental feature of modern engineering and play a major role in MBSE. An information model for geometry and topology was standardized in ISO 10303-42, part of the generic core model. This core model has been used in several APs, most recently in AP242, and has been implemented in most proprietary CAD software systems. The model from ISO 10303-42 is also used in ISO 16739-1.

9.8 Digital twin (DT)

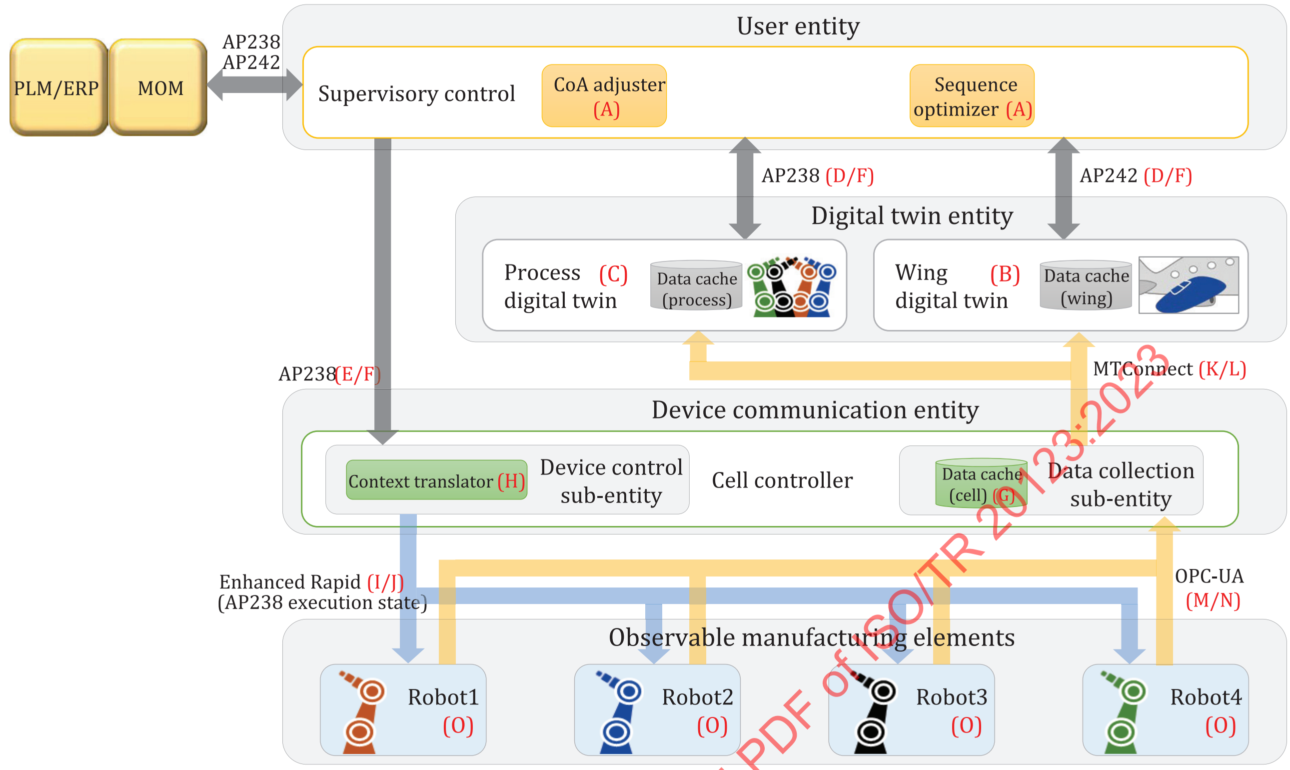
The fundamental characteristic features of a DT are a physical object, a virtual representation of the object, the avatar, communication channels from the object to the avatar and from the object to the avatar. This two-way data stream is termed the digital thread. ISO 23247 DT for manufacturing is a new standard that provides guidance for the design of a DT that can meet the requirements for an NDE. The key aspects of this framework are illustrated in Figure 12.



NOTE Source: ISO 23247-1:2021, Figure 2 — IoT framework for DTs in manufacturing.

Figure 12 — Framework for a digital twin (DT) for manufacturing

Successful applications of this framework have been demonstrated by three use cases. One of these use cases is illustrated in Figure 13. The observable manufacturing elements can be either any operation or sensors and the principal control information flow can be managed by other standards that can represent processes other than machining.



Key

Models

→ product/process

State stream

→ plunge complete, etc.

Instructions

→ G-Codes, etc.

NOTE Source: ISO 23247-4:2021, Figure B.2 — Dynamic scheduling of robots.

Figure 13 — Types of observable manufacturing elements in the reference architecture of the ISO 23247 series

9.9 Long term archiving (LOTAR)

An important feature of information management for the nuclear sector is the requirement for long term retention of the data, effectively forever for the management of nuclear waste. A method for archiving digital data should therefore be a fundamental part of the management of information for a digital ecosystem and of MBSE. The problems arising from legacy data were identified in several national surveys.

A framework for the archiving of digital data is described in ISO 14721[28]. The framework identifies six stages in the archiving process:

a) Ingest: input data records plus metadata to enable them to be found in the future.

b) Data management: editing and quality control of the input. Quality management requires conformance to a specification.

c) Storage: physical storage, including back-up and migration to new media when required.

d) Preservation planning: ensuring that that the data is not just a stream of unreadable digital bits when future access is required, and the originating software and systems are no longer available

e) Access: finding records in the archive and distributing them to appropriate users.

f) Administration: O&M of the archive.

The requirements of stage b) can be satisfied with the specifications defined in standards developed by ISO/TC 184/SC4. Stage f) requires that the digital representation should be independent of proprietary software. Avoiding the problem of legacy data can therefore be achieved with the preservation of both the semantics and the syntax of the data representations in standardized models from standards developed by ISO/TC 184/SC4.

This subject also is strongly related to record management as described in 7.1.

9.10 Alternative methods, standards and tools to be explored

The nuclear industry, as in many industries, is facing a multiplicity of models and standards to implement a full MBSE.

The nuclear ecosystem is also facing challenges to integrate legacy data repositories and applications for the efficient management of the defined use cases in a context when there are many existing standards, and new ones developing with the IIoT and the implementation of the DT.

To overcome these challenges, the nuclear industry needs, on one hand, a sustainable approach to tame this diversity in the long term, and, on the other hand, to adapt to new business requirements and to new technological capabilities, which are changing quickly.

For future standardization works supporting the digital nuclear ecosystem, keeping an open mindset is important to leverage possible new approaches to integrate data from heterogeneous models and to benefit from the future specifications produced by initiatives of the industry of the future e.g. the specifications of the Asset Administration Shell of Industrie 4.0, completed as necessary by specific requirements for a use in a nuclear context.

10 Proposed strategy and high-level road map

10.1 General

This clause gives proposals for the scope and objectives for a future Technical Report for an NDE.

This clause gives the main lines of a strategy and high-level roadmap, which will need further work for the identification of the steps to accomplish the vision described in this document.

The key topics include the following:

- Future guidance / standards for an NDE should
  - define a clear strategy and roadmap for adoption,
  - define a clear business case for adoption of NDEs,
  - be based on four key pillars:
    - configuration management (CM),
    - requirements management,
    - breakdown structures, and

    - reference data management,
  - make use of MBSE approaches,
  - make full use of the significant volume of existing standards, guidance and methods available from other industries,
  - include a strong, simple, and shared framework,
- In addition, the future NWI should consider inclusion of
  - Establishment of a common information standard setting out the information required and data formats for common asset types in the nuclear industry to improve efficiency and aid interoperability.
  - Establishment of a clear summary of the standards and guidance relevant to digital ecosystems would allow clients and suppliers to more quickly identify the standards and guidance that exist and identify where there are options to consider.
  - A definition of how the distinct information requirements related to highly specialized equipment for the nuclear industry can be met.
  - A definition of how best to integrate the many different disciplines (e.g. civil, architectural, mechanical, electrical) involved in the nuclear industry. is also critical. This fact is supported by the emphasis on the systems engineering for nuclear facilities described in this document. The integration process of the shared information depends on the structured set of data, which is practically achieved by using standardized breakdown structures.

10.2 Proposed strategy

The strategy should be defined according to the high-level requirements and generic use cases described in 5.6 and based on the structure of the ecosystem of actors and means to implement the required data management throughout the lifecycle.

Breakdown structures of the plant according to different aspects, functional, product, location, etc. should support the organization of the data and their computation for human decision.

Properties play a central role from the expression of requirements to the health monitoring of equipment, thus, the representation of properties according to standards is a key need for the nuclear industry, which should analyse existing standards on property representation in order to identify some specificities of the nuclear industry as safety classification of equipment or properties linked to the physical and chemical processes involved in nuclear processes, their operation and control.

The set of linked breakdown structures of the plant is the basis for the alignment with the standardization of the processes and also for the implementation of management methodologies related to planning, cost control and scheduling.

The context of implementation of the strategy, which for a new build, is a plant in operation or in dismantling, will impact the tactical approach and the organization of the feedback from these different contexts of implementation.

The strategy is to launch a process of standardization whatever the type of facility and whatever the phase of the lifecycle, following the same conceptual framework developed in the 10.3, with sharing of the feedback and of the respective requirements of the actors.

The projects of refurbishing existing plants either to extend their life span or to fulfil new requirements, or both, can be the opportunity of standardization activities in implementing new approaches supported by DT technologies with clear safety improvements and economic benefits in the refurbishing phase and subsequent phases of operation and dismantling.

New build (e.g. of an SMR), is an opportunity to implement advanced methods and tools from the beginning of a project with a handover of the created knowledge in design and construction phase of what will be useful for advanced ways of operating and maintaining and dismantling. This will be supported by new skills in client and contractor organizations. A roadmap for developing these skills should be provided in order to make this change feasible.

Dismantling projects and exceptional site cleaning projects will be the opportunity to implement a specific data model to support the corresponding activities and to identify the value of data produced in previous phases of the lifecycle of a plant (e.g. design data, O&M historical data). Standards will have a great impact on the safety and cost of corresponding operations and of management of the generated waste to be disposed.

The viability of the vision given in this document is mainly related to two parameters:

- The return of investment (ROI) of the standardized principles, methods and tools proposed for the implementation.
- The collective abilities and individual skills of the actors involved in modelling and in using advanced technologies to address their business needs.

To this end, a focus on the following priorities is suggested:

- Define a structured roadmap with standardization activities regarding new build, currently operated plants, shut-down plants, plants being dismantled.
- Propose a methodology to generate breakdown structures, with an illustration for a PWR power plant, which will be helpful to identify which standards of properties representations are needed and which kind of formats should be specified to support specific processes and be available for more generic processes.
- Specifically analyse the situation regarding the knowledge and requirements currently in documents or various data bases to assess the means in order to make them available through, for instance, advanced methods in NLP or in data and applications integration with the validation and decision by discipline and safety experts. Define the abilities and skills of communities needed to carry out the actions described hereabove.

A separate roadmap should be defined to sketch the internal and external stages of maturity to be able to execute the standardisation activities.

The proposed programme is based on the intertwined four pillars described above in this document and is business oriented. It is an ambitious program, which can be realized by phases and thanks to opportunities to address the identified priorities. Its funding is to be decided by the main industrial nuclear stakeholders after assessing its value for the considered projects. Its full success will be conditioned by the sharing of the lessons learned at each step of the lifecycle by all the actors of the ecosystem.

10.3 Strategic structured roadmap for future standards development

10.3.1 General

The future work items for developing NDE standards are grouped into three major categories:

- A strong, simple, shared framework based on the main concepts of systems engineering and on the four pillars to enable MBSE.
- The methodology of application.
- The technological guideline as depicted in Figure 14.

A specific effort will be needed to share principles, methods, and tools to share knowledge and manage requirements in a digital environment.

A strong, simple, and shared conceptual framework will be defined in the first category to comprehend all relevant concepts and issues that facilitate a common understanding of the NDE.

A set of management methods, technical methods, and viability measures in terms of the value chain will be then specified in the second category based on the framework. Priority in identifying these methodologies is given to the most influencing business functions to boost industry implementation.

Finally, in the third category, practical guidelines to implement the methodologies will be published. The guidelines can promote the practical implementation of NDE standards and other existing standards in a collective and harmonized manner.

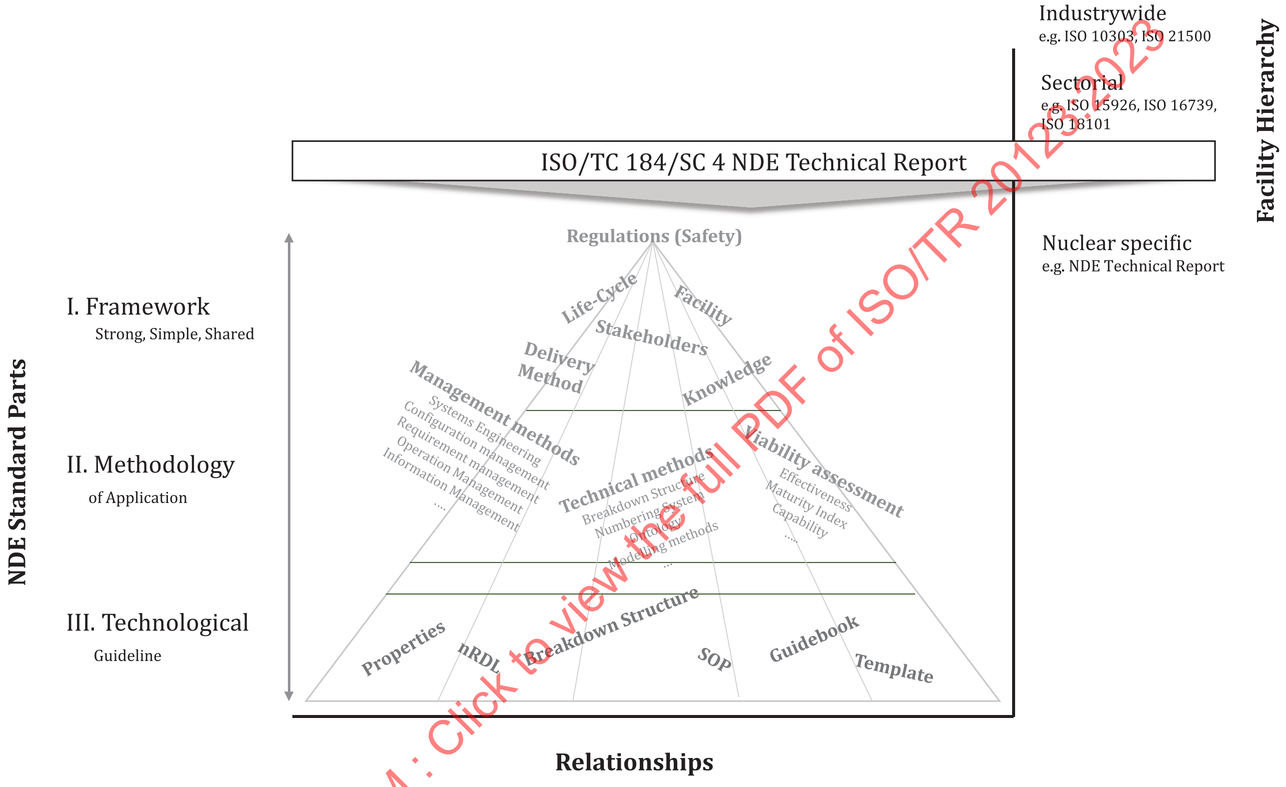


Figure 14 — Roadmap for digital ecosystem standards

10.3.2 Strong, simple, shared framework

It is essential to have a strong, simple, and shared framework in order to:

— identify and share a mutual understanding of the business objectives;

— develop a methodology to apply this framework to the specific current contexts of the steps in the lifecycles;

— propose practical guidelines and roadmap to boost the practical implementation of the standards adopted for the NDE.

Many nuclear industry standards specify engineering subjects or data issues. Nonetheless, nuclear facilities within the ecosystem have a pragmatic value-chain in which the facility owner-operator and all other participants interact throughout the life cycle from the planning to the decommissioning.

Therefore, effectively facilitating the information exchange in the nuclear ecosystem will be enabled by a high-level conceptual framework encompassing all relevant issues to share a common understanding. This framework can provide a shared starting point to implement existing standards further collectively. It also allows distinct requirements of the nuclear industry to be specified.

This framework of the NDE will specify a conceptual model of components and relationships that represent information requirements to facilitate data exchange and sharing across the nuclear ecosystem in a structured and automated manner.

10.3.3 Methodology of application

The fundamental methodology for information exchange in the NDE defines areas of standard applications based on the NDE framework. The methodology has three main components: management method, technical method and viability.

The first component of the management method is a value chain that creates and delivers information within the ecosystem. Examples of nuclear industry functions include system engineering, requirement management, CM, performance management, operation management, and reference data management.

Secondly, the technical method is a tool or mechanism that supports the management method. NDE technical methods can include breakdown structures, classifications, high-level ontology, and collective skills.

Finally, the viability addresses the practical effectiveness in implementing NDE information sharing. Procedures, rubrics, and indices measuring the effectiveness can provide directions to improve NDE standards' implementation. The maturity index or capability index are the examples to be developed. This issue of viability can also identify insights for the standard development efforts. Priority in identifying standard methodology is given to the most influencing areas of the real-world practice.

10.3.4 Technical guidelines

Defining guidelines for the NDE is a complicated task. Therefore, a top-down and goal-oriented approach is planned first to comprehend all related issues. Based on the defined framework and methodology, technical guidelines will be developed by specifying how to implement them.

Technical guidelines include properties, reference data, standard operation procedures, guidebooks, and templates required to communicate specifically within the NDE. Strong emphasis is given to the concreteness and practicability of these technical guidelines to support industry implementation.

A challenge will be to take care that companies. using the legacy systems of today and which are mostly used to a document centric way of working, can identify which steps to make in their specific situation and specific stage of maturity.

10.3.5 Future work items

The strategic roadmap for future work of the NDE, as depicted in Figure 10, focuses on the following objectives to better promote industry implementation:

- information exchange standards based on unique managerial requirements of NDE;
- high-level standard identifiers for frequently and commonly used components in NDE;
- comprehensive features to encompass all related disciplines of a facility.

One of the unique characteristics is the homogeneity of limited stakeholders in NDE, as opposed to the fragmented nature of the general construction industry. It makes it challenging for the nuclear industry to implement global standards.

Available standards are industry-wide (e.g. the ISO 10303 series) or sector-specific (e.g. the ISO 15926 series) from the perspective of facility-specific requirements. Some other existing standards are ICT-based models (e.g. ISO/TS 18101-1) regarding business management requirements. As a candidate measure to address these limitations of existing standards, this document has derived the inference that a systems engineering approach focused on safety issues is an integral part of the highly regulated nuclear industry. In this context, NDE standards pursue providing facility-specific solutions based on ecosystem business issues with management methods.

Among those facility-specific solutions, selected high-level physical components must be specified with the standard identifier (e.g. reactor and pressurizer). These identifiers are used extensively in everyday practice worldwide. Despite the significance and necessity of these identifiers, no comprehensive global standard currently exists. Common identifiers can be used by a variety of applications, including project numbering systems, breakdown structures, as well as properties for various transactions. The selection of major standard components will be based on effectiveness evaluation to boost industry implementation, as it is difficult to specify a massive number of the components.

The NDE-specific features coupled with management methods enable machine-readable and information-rich sharing. One good example is a numbering system (e.g. turnaround work items) that uses the breakdown structure with standardized identifiers. Based on a flexible standard numbering system, a wide range of datasets and documents can be exchanged. It also facilitates using existing industry-wide or sector-specific standards collectively to include all components from various disciplines. For example, a numbering system can combine the NDE standards (NPP equipment) to the ISO 15926 series (process elements), ISO 16739-1 (building elements), ISO 21500 (management issues), etc.

10.4 Orientation for managers and practitioners of the nuclear industry

10.4.1 General

The nuclear industry as a modern and advanced industry is in the front line to solve interoperability challenges faced by other industries.

This challenge will be addressed at the same time at the organizational, methodological, and technological levels.

The nuclear industry has intrinsically the specific features of an industry of the future with the organization of the recycling, the reprocessing of burnt fuel and its ability to produce low carbon energy of the future in amounts which correspond to the needs of the global population.

The data, information and knowledge produced throughout the phases of the lifecycle of a nuclear facility will be made available to all the actors when useful for the safety and economic performance and to enable the implementation of the circular economy principles for the whole nuclear ecosystem.

It is recommended that those active in the nuclear industry rely on the basics for a successful interoperability of the ecosystem to lead conceptual, methodological, and technological advances focused on practical benefit of interoperability of the processes crossing the various organizations of their ecosystem.

The following subclauses intend to bring some light on the way forward in the context of the nuclear industry.

10.4.2 Systems engineering

Systems engineering brings a common conceptual framework to diverse systems. Requirements management is a thread for all the concerned actors throughout the lifecycle of a nuclear facility.

The importance of the relations between sub-systems, emergence, and submergence of properties from one level of system to another one, diversity of the systems and of their specific laws should be familiar to those involved in the nuclear sector.

Moreover, the concept of system is also fruitful for developing information systems and for the understanding of an organization, in this case the ecosystem of the actors involved in the complete lifecycle of a nuclear facility.

The culture of safety in the nuclear ecosystem is a strong asset with safety requirements management, its strong principles shared and concretely implemented by the nuclear community at the physical, informational, and organizational levels.

The effort should be focused on the meaning of the requirement for understanding what a generic requirement is and how it can be made formal to take the greatest benefit of the computability of formal requirements. Practically, this will be a clear lever for investment made in information management.

This mindset will operate and be fruitful throughout the lifecycle.

A common framework of understanding of the physical system, of the information system and the ecosystem will be of great benefit to deeply map the corresponding structures and their synchronized transformations.

This framework should be easily shared by the manufacturing and construction domains and will be helpful to define common core terminologies and reference architectures.

10.4.3 Methods and knowledge representation

Standardization is the core methodology for industrial efficiency and standards gather knowledge to be reused and created in the projects.

Economy of nuclear industry as for other industries is driven by standardization and by knowledge accessibility.

The standards of industrial data will reflect the standards of physical nuclear systems, structures, and components.

In a digital ecosystem, the main challenge will be the availability of the knowledge in internal or external Standards Machine Accessible Readable and Transferable (SMART).

Industrial projects in the aerospace, automotive, construction and oil and gas sectors are developing standard models and reference data libraries which will offer standards as a set of computable requirements, which support the automation of many tedious tasks of managing data and their quality.

The nuclear industry should benefit from all these advances, complete them as necessary to consider its specificities, and has strong interest in the interoperability of these models and reference data libraries.

10.4.4 Impact of digital technology on standards for the nuclear ecosystem

Hopefully, technology and technological standards will enable the interoperability of standards from various domains and dealing with specific contents.

The development of the IIoT, the availability of standards to link data fit with a distributed knowledge in all the parts of an ecosystem, where each actor has responsibilities in its own domain and supports the connexion of the physical systems and the information system for the proposals of the best decisions for the organization in charge.

Semantic technologies, already used in advanced industrial projects in process industries and being explored for nuclear knowledge management,[29] need further work to benefit of all their potential, combined with IIOT standards.

The efforts made during past years and the lessons learned from the implementation forum, from the feedback of projects such as CFIHOS[30] for digital hand over of data, DEXPI[31] for exchange of P&IDs, READI[32] on formal requirements as well as other initiatives in manufacturing and construction, will benefit to nuclear industry as a confirmed industry of the future.

Annex A
(informative)

Nuclear power in China

A.1 Background

China has a very comprehensive nuclear supply chain, and a well-recognized fastest growing nuclear power industry in the world for the time being. As of June 2021, mainland China has 50 nuclear reactor units in operation and 12 units under construction, Taiwan has 4 units in operation and 2 units in decommissioning. Major OO in the nuclear power sector in China are:

- China National Nuclear Corporation – CNNC
- China General Nuclear Power Group – CGN, formerly the China Guangdong Nuclear Power Group
- State Power Investment Corporation – SPIC
- China Huaneng Group – CHNG
- Taiwan Power Company – TPC

Major nuclear reactor types owned and operated by these OO are:

- CNNC – CNP-300/600, CANDU 6, VVER-1000/1200, CPR/ACPR-1000, M310, AP1000, Hualong-1
- CGN – M310, CPR/ACPR-1000, EPR-1700
- SPIC – AP1000
- TPC – BWR-6, WE 312 3-loop

Other reactor types in operation or under construction include: CAP1400, HTR-PM, HTR-10, CARR, CEFR, EAST.

The following IT systems are in general use. In almost every area, there are endeavours to implement or develop domestic or in-house solutions, particularly in the areas of management and general technology.

Software for the creation of assets include:

- Geographic information systems (GIS) – Super Map GIS (domestic)
- Computer aided engineering (CAE) – EDF, and Westinghouse, calculation software package, NESTOR, ANSIS, Flowmaster.
- Computer aided design (CAD):
    - 3D Plant design – PDMS, E3D, PDS, SP3D
    - Process: AVEVA Diagram, SP P&ID
    - Electrical and control – EB, SP Instrumentation, CDMS (in-house)
    - Civil and structure– Revit, Tekla
    - Mechanical – NX. CATIA

  - 3D plant design review – Navisworks, T-Plant (domestic)
- Scheduling – Primavera, MS Project
- Material management – AVEVA ERM, SPM, SAP
- Product or Plant Lifecycle Management (PLM) Design Collaboration – Teamcenter, ENOVIA
- Project management – ENOVIA, SAP, IFS Foundation (in-house), ENPower (in-house)
- Commissioning – Teamcenter
- Digital handover – CNET (in-house), PIMCentre (domestic)

Software for the O&M of assets include:

- Enterprise Resource Planning (ERP) and Enterprise Assets Management (EAM) – SAP, Ventyx, IFS (retiring)
- Many in-house or domestic solutions have been implemented or developed around ERP, EAM, etc., for example, in areas such as Business Intelligence (BI) and Enterprise Service Bus (ESB), equipment reliability, experience feedback, ageing management, exposure monitoring
- Historian (Supervision Information System (SIS) is the term normally used in China) - PI
- Scheduling – Primavera, MS Project
- Digital Thread and PLM – ENOVIA, WIZ PLANT (domestic)
- Master data – ENOVIA, SunwayWorld MMD (domestic)

A.2 State of the art

Many digital concepts have been introduced into the nuclear industry in China. They also need to align with the national digital transition strategy 'New Digital Infrastructure'. The concepts in the new digital infrastructure include industrial artificial intelligence, industrial internet, internet of things on the 5G network, cloud computing and so on. These new concepts are mostly piloted with either domestic or in-house solutions.

Those digital solutions include the ZHONG TAI (middle-desk) that provides packaged data services such as material, work orders; Blockchain technology is used for personal exposure data management and so on. Other digitalization projects include:

- Intelligent construction for safety and security;
- Digital Hualong for digital handover of Hualong-1 NPP;
- Knowledge graph for the digital supply chain, experience management;
- Intelligent documentation;
- Remote diagnostics;
- Machine learning for equipment failure analysis;
- Electronic fence with location base service (LBS) and big data for proactive safety;
- Digitalization of operational procedure with mobile implementation on 5G network;
- 6D simulation consisting of 3D plus time plus resource plus environment for maintenance activities in high radiation areas.

The digital transition endeavour is generally led by a ‘Leading Group’ of the company. OO generally have a Chief Information Officer (CIO) who has operation or maintenance background and a ‘Data Section’ under the IT department.

A.3 Gap analysis

There is a different focus for data between EPC and OO, particularly on engineering data. Engineering data are important for OO but are normally used less frequently compared with EPC. Thus data tends to have poorer maintenance during the O&M phase.

There are data quality issues, particularly with master data. Many interoperability issues are actually data quality issues. Due to poor data quality, machine-to-human interfaces are used instead of machine-to-machine interfaces in many cases.

There is a reliance on point-to-point interfaces rather than the use of a unified data standard. Examples include the interfaces between civil and structure design software and plant layout design software, between EAM and ERP, between scheduling software and management software.

There is lack of support for the ISO 15926 series from key software vendors for EPC and O&M. The ISO 15926 series, the core interoperability standard for the process industry, provided essential capability of information interoperability architecture, with different implementation methods by its different parts. However, the ISO 15926 series has not gained enough popularity in live projects. One reason is that the different implementation methods sometimes confuse the industry. Too many choices sometimes mean no choice.

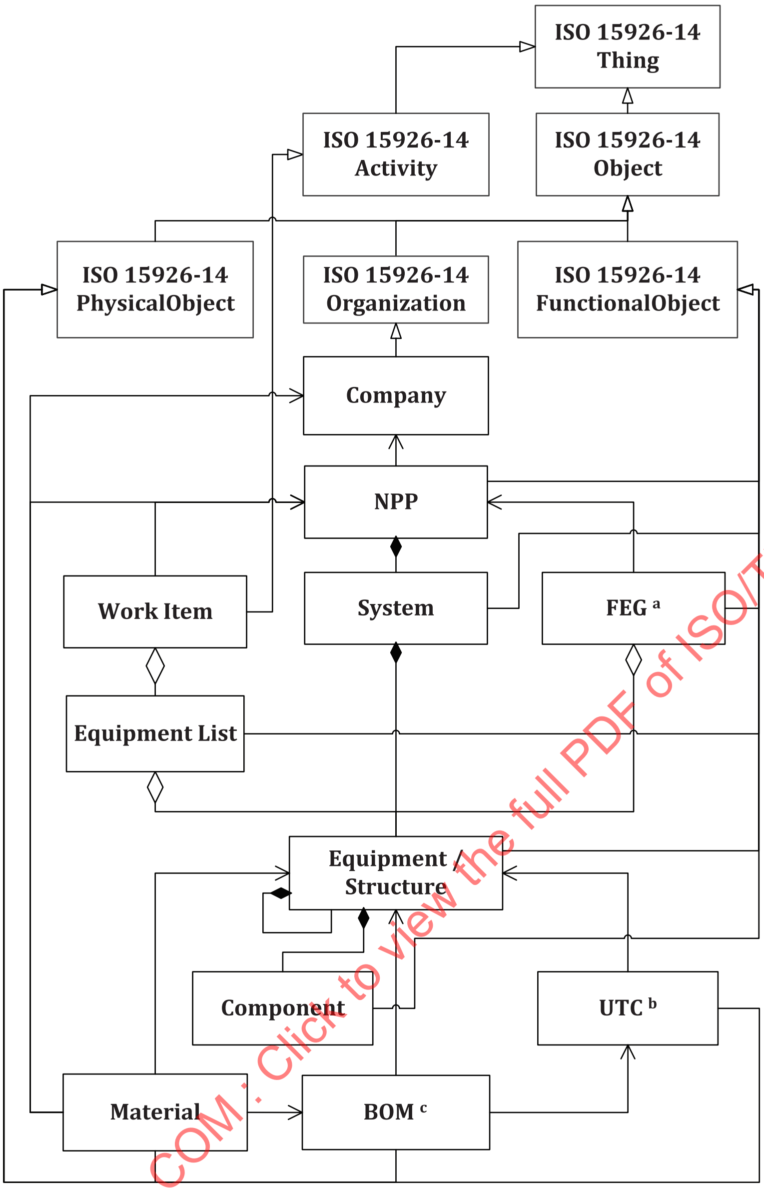
Many interoperability issues are also actually technical issues, particularly when an OO has a few different types of reactors. Many front-line people regard digitalization as a burden, as their aims are to have more intelligence to relieve their workload, but digitalization only increases their workload at the moment.

A.4 Recent significant achievements

A China Energy Standard (NB) for NPP O&M Data Requirement is under development, based on a research report approved in 2018. Table A.1 and Figures A.1 to A.3 are from the research report that identify the relationships between NPP O&M data entity and the ISO 15926 series entity.

Table A.1 — Relationship between NPP O&M data entity and ISO/TR 15926-14 entity

NPP O&M data entity	ISO/TR 15926-14 entity
Structure, System, Component (SSC)	FunctionalObject
Material	PhysicalObject
O&M Personnel	Person
O&M Activities	Activity
Measured Data	InformationObject

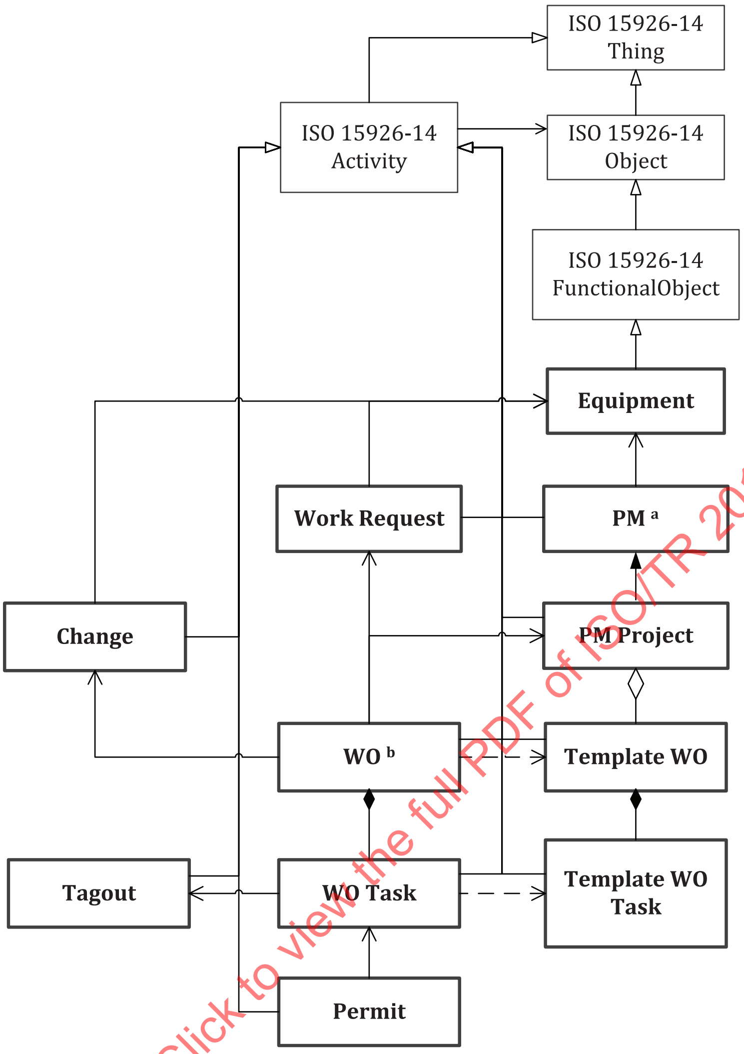


[a] FEG: Functional Equipment Group.

[b] UTC: Unique Tracking Component.

[c] BOM: Bill of Material.

Figure A.1 — Model of NPP breakdown structure



[a] PM: Preventive Maintenance.

[b] WO: Work Order.

Figure A.2 — Model of work order

GB/T 32575-2016 is China National Standard (GB) for Power Plant Engineering Data Handover that will cover nuclear power. The following diagram from GB/T 32575-2016 indicates handover information and power plant identification coding from GB/T 50549-2010, similar to ISO 81346-10, in relation to the ISO 15926 series.

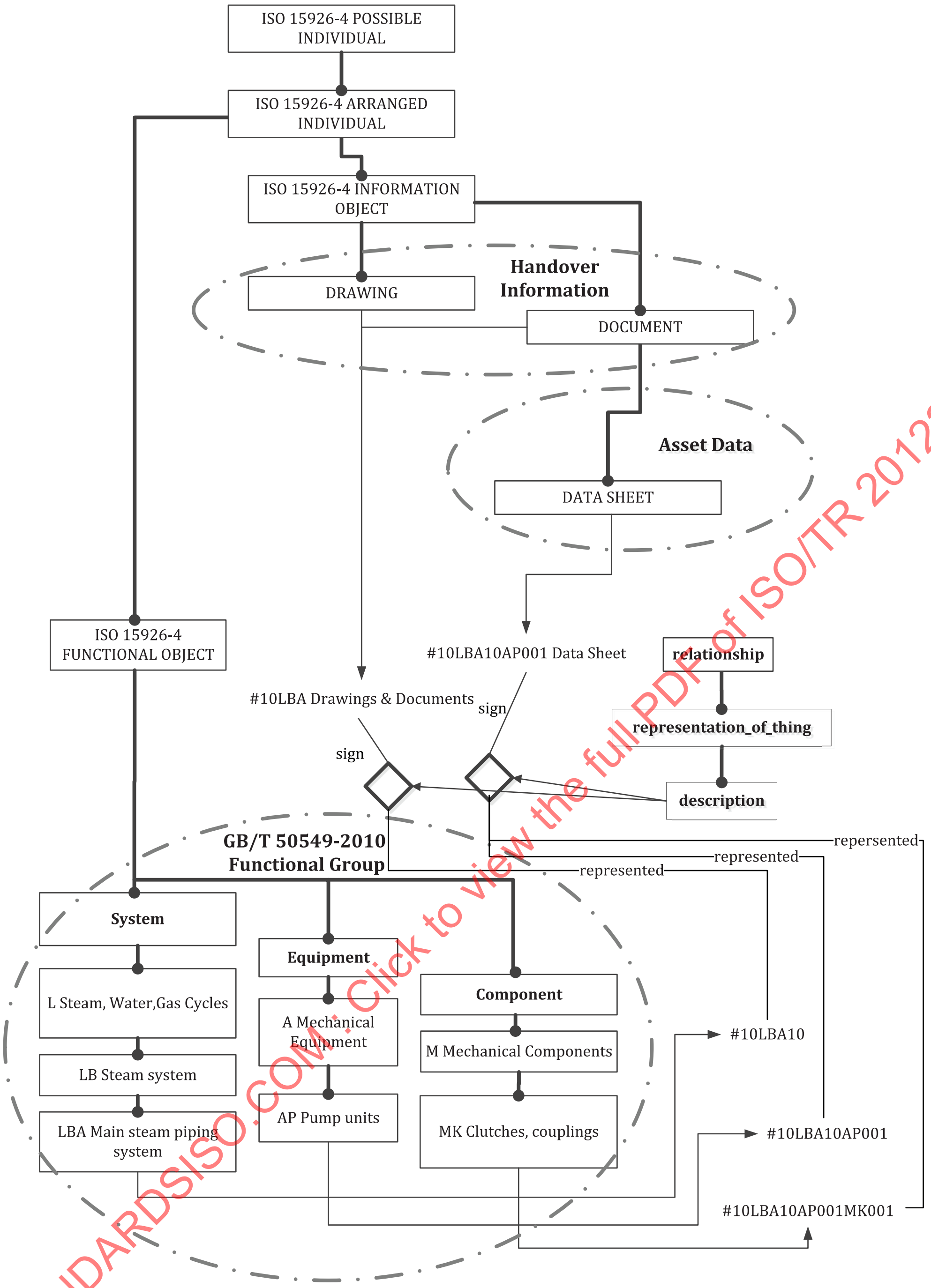


Figure A.3 — ISO 15926 series elements in the China national standard for Power Plant Engineering Data Handover

There have been digital handover efforts for units 3 and 4 of the Fangchenggang NPP, units 5 and 6 of the Fuqing NPP and of units 3 and 4 of the Tianwan NPP.

A.5 Perspectives

All key nuclear power players have a plan and organization for digital or smart or intelligent NPPs. DT is considered as a key technology for digital transition. There are discussions on whether a DT will focus on CAE and simulation or focus on the digital thread.

There is convergence of informatisation and industrialisation in China. Several related China National Standards have been published and corresponding certification system has been developed. Almost all key nuclear power players in China have been certified.

The interoperability approaches by 'old software', such as ERP, EAM and PLM, and the 'new software', such as 'ZHONG TAI (middle desk)' are different. The new software does not generally model data following the 'traditional' way by the use of current international industry standards.

A.6 Mid-to-long term view

Nuclear power is the key to peak emissions by 2030 and carbon neutrality by 2060 in China. It is estimated that nuclear power capacity has to increase by seven times by 2050 in China to achieve these targets.

To support the China National Strategy for digital or smart or intelligent NPPs, the National Development and Reform Commission issued the 13th Five-Year Plan for energy technology innovation, proposing to focus on research for the smart operation of the nuclear power infrastructure. The National Development and Reform Commission, the Ministry of Industry and Information Technology, and the National Energy Administration have jointly issued the 'Made in China 2025 -Energy Equipment Implementation Plan', proposing a breakthrough of nuclear power equipment smart manufacturing technology. The State Council has issued the 'New Generation Artificial Intelligence Development Plan', proposing to build an intelligent platform to support the safe operation of nuclear power. The National Development and Reform Commission, the Energy Administration, the Nuclear Safety Administration jointly issued the "Guidance on Further Strengthening the Safety Management of Nuclear Power Operations", requiring promoting new technologies such as informatisation, intelligence, and big data in operation and safety management of nuclear power.

A.7 Standardization strategy

There are needs to have solid use cases and examples of the use of the ISO 15926 series and other standards for NPP data representation. The nuclear industry has more balanced content: civil, structure, mechanical, E&C, piping. Though it is ideal to have a 'common language' for an NDE, it is not practical to use just a single standard for all disciplines throughout the nuclear facilities lifecycle. However, a core ontology standard is essential to achieve a minimum level of interoperability. The relatively successful standardization approach demonstrated by ISO 16739-1 can be taken as a reference. It is recommended to start with a relatively simple scenario and small coverage, gain popularity first, then increase coverage with more complexity and more advanced technologies such as the SW. The ISO 15926 series and other standards should be promoted to key vendors of software for O&M. There is an expectation of a unified and easy-to-use set of the ISO 15926 series rules or constraints on semantics or syntax, together with a common, simple nuclear RDL similar to CFIHOS as part of a nuclear ontology, to help to solve some simple but real interoperability use cases first.

Annex B
(Informative)

Nuclear power in France

B.1 Background

According to the IAEA Report,[33] in 2019, in France, 58 PWR reactors were in operation, 1 PWR is under construction and 12 were shutdown. The 2 PWR 880 MWe reactors of Fessenheim were stopped in 2020.

The experimental NPP of Brennilis, moderated with heavy water and cooled with carbon dioxide (HWGCR) was shut down in 1985. This nuclear plant marks the first decommissioning of a complete nuclear power station in France. EDF and CEA announced their intention to make this a transparent process so that it can be used as a model for future decommissioning operations at other plants.

Superphénix (Fast Breeder – SFR) is on the dismantling path with work on the vessel.

The dismantling of the Research Reactor Ulysse, at Saclay, was finished in 2020. France has restructured its civil nuclear sector and deploys projects for several kinds of power stations: SMR (fast breeder 50 MWe and PWR 160 MWe), ATMEA (3 loops EPR 1 000 MWe), EPR (1 600 MWe), EPR 2 and has studied a 600 MWe fast breeder (Astrid).

France is also hosting the ITER [34] project and delivers major components.

For aging study, EDF, Electricité de France, has built the VeRCoRs,[35,36] 1/3rd-scale reactor building which becomes a test laboratory.

Final disposal for long life waste by the Industrial Centre for Geological Disposal CIGEO[37] is on the way.

Dismantling activities are undergoing industrialization processes.

Fuel manufacturing and reprocessing made significant progress regarding accident tolerant fuel and improvement for U5 fresh fuel (EATF fuel assembly with a first loading in the USA) and MOX fuel plants performance.

The sector's restructuring has a good indicator: the setup of the French Group of Nuclear Energy Industry, Groupement des Industriels Français de l’Energie Nucléaire (GIFEN[38]) which contributes with the existing network of professionals already organized in different French regions and federated within the cluster Nuclear Valley Association. The French Nuclear Society for Science (SFEN) is still active to maintain a high level of expertise and share knowledge.

Difficulties encountered in the construction phase of the EPR projects demonstrated that the French supply chain suffered from the lack of projects over the past 20 years with skills, competences, and know-how issues in welding, handling, building erection, large project management with evolving regulation (ESPN[39]). This must not hide the performance of nuclear engineering and operations, since the Taishan 1 EPR, e 1 750 MWe plant got the best availability factor for year 2019, followed by PWR N4 Civaux in France – above 80 %.

COVID and the containment period have shown a good resilience of nuclear power supply due to good decisions and adaptation from operators and reactivity of NPP Services companies which have to deliver services under new constraints, providing a framework of innovative solutions for service continuity during outage.

The challenge for the French nuclear industry is to still improve its economic efficiency for carbon-free power generation without any compromise to safety. Several topics can contribute to this target:

- skills and competencies and training including the attractiveness of the nuclear industry directed toward young workers;
- knowledge management including access to external experts and cross-generation mentoring;
- component standardization;
- system engineering;
- R&D and collaborative project on challenging topics (e.g. new materials, additive manufacturing, new instrumentation and control technologies);
- operational excellence in all practices: engineering, manufacturing, large project, operations, maintenance, dismantling.

Digital transformation remains a key enabler for all of these topics. Digital transformation is related to: network and infrastructure, software, data, cyber security, standards, intellectual property, regulation and the related impacts in terms of governance and operating model.

For each of these aspects, sovereignty is at stake.

B.2 State of the art

Each major stakeholder in France (EDF, Orano, CEA, Framatome, Technicatome, Andra) has its own digital transformation program covering the whole nuclear lifecycle: engineering, new built and installed base modifications, manufacturing, erection, services, including operations, commissioning and dismantling. Complementary to those programs, GIFEN is setting up a digital program focusing on collaboration within extended enterprise concept and interoperability pre-requisite.

Digital continuity is then a major topic internally for each company and also for the ecosystem. Some fundamental standards such as the ISO 15926 series can contribute to ensure interoperability in these two dimensions but are not covering all business activities right now. EDF developed in early 2000 the MUDU data model[40,41]to manage all the engineering data for the EPR project. For instance, services activities have not been addressed by any standard yet. A GIFEN project, eDRT,[42] for electronic Work Packages (eWPs) is currently addressing this point in the domain of reactor maintenance. A document becomes a data structure, usable by different devices, such as paper or web applications (e.g. tablets, smartphone, laptop).

Digital continuity is then a major topic internally for each company and also for the ecosystem.

Digital management of safety requirements are now centralized in a unique collaborative "ESPN digital" platform for all stakeholders, e.g. regulations and safety authorities, testing, inspection and certification (TIC) services companies, operators, manufacturers.

Major digital programs currently address PLM and BIM, DT, knowledge management, evolution of references code, digital transformation and the deployment of information systems allowing big data and data analytics, as well as IIoT and Future Field Worker.

Blockchain is under testing between EDF and Framatome, for instance, for data source authentication and traceability for tamper-proof recording of tests results on materials.

COVID containment has shown that any digital collaborative tools were more than welcome: VPN connector increased sharply as an enabler, web-based applications, mixed reality or immersive applications and remote monitoring and expertise.

B.3 Gap analysis

The main issues are related to performance:

- How to improve effectiveness with digital continuity across the physical flow of materials in a plant or with customers?
- How to improve hands-on work time with digital helping to shorten lag time by improving synchronization with our customer and suppliers or to avoid wasting time to find a tool, a product or person?
- How to avoid redoing work with faster data process and immersive capabilities (late change, maintenance to design)?
- How to avoid displacement or moving time by giving access to legacy data everywhere (having the right data, pushed to the right person at either his or her place at the right time)?
- How to avoid error with non-ambiguous language, process and data concerning a very complex system?
- How to avoid failure: Scram, I&C, or human failure, customer data leak, threat and computer abuse?

It is obvious that all solutions addressing these issues require sustainability. Although digital technologies are evolving very fast, nuclear industry assets are long-term. International and open standards are the best way to manage this sustainable development of digital assets for these purposes.

B.4 Recent significant achievements

Framatome (formerly AREVA NP) developed the AiRE[43] platform supporting the ISO 15926 series and with capabilities to edit and compare RDLs and has investigated an Ontology Driven Information System for NPP.

EDF has developed a core data model and a shared catalogue (MUDU). The mapping of this data model with ISO 15926-2 core data model allowed the automatic generation of an RDL.

Tools and services for ontology alignment have been further investigated to compare the generated RDL with the ISO/TS 15926-4 RDL and the PCA RDL.

Efforts made towards paperless deployment helped to define critical data. The eDRT project is a standard for data exchange among operator, maintenance entities (customer, service providers) and the supply chain. This of course needs to clarify the language and terms (RDL). Strong transformation programs towards digitization of document and related operating procedures are being deployed across industrial sites such as in Orano from mining to uranium transformation sites and up to dismantling of installations. A strong user experience (UX) of operator’s journeys warrants a good adoption with the help of a network of French start-ups like Siteflow (www.siteflow.fr) dedicated to support industry specific requirements and regulations with compliant mobile applications. This program also engages a large deployment of high-speed wireless (WIFI) and IOT (LORA) networks across main plant workshops and cells where real-time connectivity is needed to improve efficiency.

A collaborative initiative between nuclear waste producers including EDF, CEA, Orano and Andra started to define standards for waste management data exchanges. Waste information management systems are being modernized and extended inside each enterprise and a GIFEN digital project “waste digital continuity” will accelerate the path to digital transformation across forecast, planning, and logistics operations processes.

Major digital transformation programs (SWITCH at EDF, EPR II at Framatome) also require the definition of a comprehensive and long-term data model for each system, equipment or room. This is continuously ongoing work, especially to allow to connect 3D CAD models and virtual reality applications.

Waste information management systems are being modernized.

For the French ESPN regulation, a collaborative platform has been set up in the last one year (ESPN Digital); it is used for accelerating the verification of conformity and encompass mobility for site inspection in manufacturer's premises.

Other platforms are also launched for big data analytics, such as Curiosity which received the SFEN Innovation award 2020, but COTS, such as Power BI are also used to deliver a head-up display of complex activities (maintenance activity on a wide set of reactors – Framatome Installed Base).

For the design of complex chemical and mechanical transformations of Uranium and the reprocessing of used materials installations, Orano engineering is already using a comprehensive and integrated suite of EPC applications for 1D, 2D & 3D modelling. The DT transformation program of Orano is bridging the digital discontinuity gap of the handover from engineering to O&M using aggregation of engineering, asset lifecycle and real-time data.

Most large companies have moved from document centric to digitalized documents, with NLP for more efficienct access to the asset, and paperless and now are moving to a data centric approach which relies on common language, data model and standards.

Orano is actively pursuing a data value-based transformation program including: a large data and IA training plan, a set-up of distributed data governance organization, the build of a data architecture facilitating collection and access to industrial data, and an agile management of a portfolio of data analytics and data sciences projects in engineering, operations and services activities.

During COVID containment, solutions for remote expertise were established. As an example, an American supplier had to travel back to the USA before border closure. The company left their devices and process running, had a view on their local SCADA and were able to diagnose the process and talk to onsite workers in the fuel building for process tuning. These examples show that digital solutions are found for many issues. However, for some of them they need to be industrialized to become enablers. For that purpose, standards are also required.

B.5 Perspectives

In France, several initiatives have been launched since the signature by the French government of the strategic plan for the nuclear sector in January 2019[44]: “Usine Nucléaire du Futur”, GIFEN, GENESIS, ESPN Digital, eDRT at the Digital Commission and Reactor Digital Twin at the R&D Commission are collaborative and digital initiatives at the sector scale. These programs aim at delivering a nuclear promise of competitiveness, attractiveness and future carbon-free power generation for electricity and hydrogen with a continuous focus on safety, our DNA.

The funding of post-COVID crisis through France's recovery plan[45] will support nuclear industry (470 M€) for the next three years.

B.6 Mid-to-long term view

Waiting for a policy decision from the French government for nuclear new build, which should be made in 2022, the export market is a target in Eastern Europe, Asia, the European Union, USA and UK.

Systems engineering is being deployed for new programs of NPP and will become the rule with a trend towards MBSE.

Research and development efforts are being made:

- on the neutral exchange[46] and long-term management of 3D models including visualization purposes (web3D-based[47] xR) of complete digital mock-up of a NPP using international and open standards;
- on the use of graph databases[48] to navigate in the data of a NPP;

- on the digital reactor or DT following the development of the open-source simulation platform SALOME by EDF and CEA;
- on quantum computing for understanding the impact on reference codes;
- on high performance computing with cyber and blockchain.

B.7 Recommendations regarding the standardization strategy

The capability to handle several reference repositories is of course of major importance in nuclear engineering, but also in I&C, industrial protocols, and a remote platform for services.

We suggest the following recommendations:

- Establish a shared radar chart to share in the NDE a view of the standards according to their level of adoption and of maturity.
- Create the conditions of interoperability with reference repositories as a nuclear RDL, e.g. data.NDE.org, with the associated services of access and change management.
- Focus on use cases as synchronization of installation and civil works digital mock-ups.
- Specify solutions for LOTAR, which is a regulatory requirement in the nuclear sector for all the activities important for safety.
- Specify sustainable solutions for the NDE:
  - enabling the reuse of the existing knowledge embedded in the currently used data bases;
  - supporting and tuned with advanced engineering methods as MBSE;
  - robust to future needs and other changes;
- Work on explainable AI for NDE automation on image collaboration at international level.
- Develop a sovereignty policy allowing for collaboration at the international level.
- Improve prediction capabilities for operators dealing with more renewable injection in the grid (flexible operations with better management samarium/xenon and borication or grey-rod management with advanced I&C).

Annex C
(informative)

Nuclear power in Japan

C.1 Background

Japan needs to import about 90 % of its energy requirements. Its first commercial nuclear power reactor began operating in mid-1966, and nuclear energy has been a national strategic priority since 1973. This came under review following the 2011 Fukushima accident. Currently, there are 33 operable reactors, 2 reactors under construction, and 27 shutdown reactors in Japan.[49]

C.2 State of the art

C.2.1 New build

After the Fukushima accident, all the construction projects were suspended and are waiting permission to start up again based on updated regulations. Several new projects have been planned but no concrete schedule for building new NPP has been announced. However, to maintain the ratio of nuclear power generation to at least 20 % by 2030,[33] construction of new NPP is needed. The main obstacle to build new NPPs is the heavy cost for safety facilities so SMR with passive safety are the candidates of future NPPs.[50] Existing IT systems for process and instrumentation diagrams, plant 3D CAD, instrumentation and electrical diagram for the current power plant design should be inherited and enhanced to the new type of NPP design.[51]

C.2.2 Operations and maintenance (O&M)

Eighteen plants are in various states of approval for restart by the New Regulation Authority (NRA) from 2012. The reactor restarts are facing significant implementation costs ranging from $700 million to $1 billion per unit mainly for the reasons of safety measures. The NRA announced it would not extend deadlines for utilities building facilities to meet new anti-terrorism guidelines. The ruling affects at least ten reactors and could potentially see operating reactors temporarily shut down.[50] The Reactor Oversight Process (ROP), introduced by the US Nuclear Regulatory Authority (NRA), requires the means to collect information about licensee performance, assess the information for its safety significance, and provide for the response from the appropriate licensee and the regulatory body. In Japan, free access by the NRA to all facilities and activities at any time is required for the purpose of the audit. A large amount of inspection data should be managed and efficiently retrieved corresponding to any queries from NRA.[52]

C.2.3 Decommissioning

Decommissioning should be done with the budget saved during the operation of each NPP so avoiding cost overruns within a scheduled decommissioning duration are very important issues for each utility company.[53] Radioactive inventory data during plant operation should be properly mapped to plant component data and should be reflected onto data from either dismantled or segmented waste fragments that should be managed in a controlled area for several hundreds of years.

For the decommissioning of the Fukushima site, many new technologies should be developed for dismantling the unprecedented accidental site. This project is organized by the International Research Institute for Nuclear Decommissioning (IRID).[54]

C.3 Gap analysis

For new build, experience of plant construction is decreasing. The inheritance of knowledge for plant design and construction is therefore critical.

For O&M, Japan refers to the reactor oversight process (ROP) of the US NRC. The ROP is the regulatory framework that is a risk-informed, tiered approach to ensuring plant safety.[52] Japan's new nuclear regulation has applied from 2020, and a licensee's responsibility is to constantly improve the safety of its facilities. Many inspections are expected to correspond to those activities so the management of these activities and equipment reliabilities with a feasible plan is important.

For decommissioning, a concurrent decommissioning project will be expected. A feasible and economical plant should be made for a successful project with no final disposal site for the new future. To do so, a precise estimation of radioactive waste is required and a facility for the interim storage of waste is needed.

For the decommissioning of the Fukushima site, new technologies should be developed for removing fuel debris from an unprecedented and very high dose-rate area by using remote operating robotic systems.

C.4 Recent significant achievements

C.4.1 New build

Two NPPs are under construction (Ohma and Shimane 3) in Japan. Construction of these plants are using 3D-CAD engineering and construction management system to optimize the planning of construction procedures and the installation of equipment.[55]

C.4.2 Operations and maintenance (O&M)

The Periodic Safety Review (PSR) is a continuous safety enhancement process to improve overall plant safety.[56] To achieve the objectives of PSR, plant operators need to review their operating experience as well as reassess their past review and identify findings which lead to improvements of plant safety. It is also important that regulators participate in the preparatory work of the review to identify the issues and the outcome of the review. To improve the efficiency and effectiveness of this activity, the regulators need to develop a technical information base reflecting the safety inspection carried at the sites to identify issues.

C.4.3 Decommissioning

A decommissioning engineering support system based on 3D CAD models has been developed.[57] There are essential technologies for decommissioning engineering, such as for evaluating the residual radioactive inventory, planning for decontamination, and dismantling, remotely controlling dismantling machines, managing waste processing, and measuring radiation. Decommissioning projects should proceed appropriately based on these technologies. To integrate them, the 3D geometric shapes of a decommissioning plant, functional system data, and data on residual radioactivity accumulated during plant operation should be stored in a database and shared among decommissioning support systems.

C.4.4 Decommissioning for the Fukushima site

It is important to introduce robots and remote-control devices focused on reduction of radiation exposure of workers for exploration in building, sampling, setting of measuring instruments, decontamination, shielding and transport of use materials and equipment. In August 2013, the IRID was established for R&D management organization in removal of fuel from spent fuel pools, retrieval of fuel debris and treatment and disposal of radioactive wastes including development of robots and remote-control devices. Validation tests and operator training for remote control devices for retrieval of fuel debris were also planned using a newly prepared mock-up facility.[58]

C.5 Perspectives

New build will require cost conscious design, efficient manufacturing and construction methods which support enhanced safety measures.

For O&M, project planning for a high utilization rate of NPPs should be made by shorter inspection periods and longer operation duration.

For decommissioning, precise waste estimation and its management in order to decrease the amount of radioactive waste to be controlled is very important.

For the decommissioning of the Fukushima site, remote operation technology will be needed to reduce the environmental impacts affected by contaminated water that comes from the fuel debris in the reactor buildings.

C.6 Mid-to-long term view

New build will require sustainable new NPP design and the knowledge which is inherited from the experiences of existing NPPs.

O&M will need efficient and safety O&M that is achieved by information management systems. The systems should be used efficiently for precise audit by the regulatory body.

For decommissioning, management of radioactive waste for several hundred years should be done with its traceability from its origins from permanently shut down NPPs to its waste management facilities or sites.

A working group was established for the decommissioning of the Fukushima site to assess the extent to which the recommendations of the Fukushima Daiichi Nuclear Accident Investigation Commission report were achieved.[59] In this report, three typical scenarios for decommissioning were considered:

a) the original scenario that all the waste materials are removed from site and its end state is considered as the site is used as a green field;

b) some of equipment, structures, contaminated soils, and waste waters are remained and managed with a controlled state at the site;

c) additionally, low level radioactive waste is managed with a controlled state at the site.

In the report, a) will be completed in 30 years, b) will be completed in 100 years, and c) will be completed in 300 years. The data related to radioactive waste should be managed with in the appropriate manner with proper standards.

C.7 Recommendations regarding the standardization strategy

New build requires standardization for designing and constructing safer and more economical nuclear power plants.[56]

O&M needs standardization for efficient work management for O&M within the conditions of ALARA and lower CDF.[57]

Decommissioning needs standardization for radioactive inventory data, which was from operated power plants and for waste management according to the levels of radioactivity. The levels of radioactivity are related to the final disposal method.[58] A graded approach should be taken by the regulatory body when performing reviews, assessments or inspections throughout the authorization or licensing process.[59]

The decommissioning of the Fukushima site needs standardization related to the stabilization of accidental plants and technologies for the removal of fuel debris. This kind of experience should be considered towards lessons learned and be considered on matters of preparation, operation, governance, and mitigation related to minimizing and managing nuclear risks.[60] Some of the lessons should be reflected considered for standards.

Annex D
(informative)

Nuclear power in the Netherlands

D.1 General

This survey will mainly be described from the point of view of Pallas, as the new Pallas nuclear isotope plant reflects the digitalization of new nuclear research facilities in the Netherlands.

Pallas endorses to a large extent what is stated in the IAEA report “Application of PIMs to Manage Design Knowledge through the Nuclear Power Plant Life Cycle” (TECDOC-1919[41]) and has the goal of supporting the design and construction of the new isotope reactor plant with a DT based on the so-called K-PIM. In comparison with NPPs a nuclear research and or isotope production plant is not only challenging, e.g. ageing and technology changes over 50 years in a functional steady state situation, but additionally faces changes in product (isotopes), product process and logistics through the plant due to changes in the business process and market which requires a high maturity of integration of the digitalization of the reactor itself and the digital environment of the enterprise that operates the plant.

In this context, a DT is even more important for a research reactor than a classical reactor.

D.2 Background

There are two conventional NPPs in the Netherlands: one is still operational, one is retired.

The Dodewaard Nuclear Power Plant in Dodewaard is a former NPP. The plant was in operation from 1969 to 1997. The plant is in secure containment; The demolition of the not yet dismantled, internally radioactively contaminated buildings is planned for 2045. The power plant was a natural circulation BWR, or passive-safe BWR. The capacity was 58 megawatts. The power station has been running with high availability for 28 years, connected to the national electricity grid.

In 1969 the Zeeland Provincial Electricity Production Company (PZEM) ordered an NPP. The reactor, a PWR located near Borssele, the Netherlands, was put into use in 1973. The power plant was built by Siemens KWU.

Between 1973 and 2006, the plant had a (net) capacity of 449 MW. The plant was radically modernized in 1997. This brought the plant to a standard safety level for 1997. The modernization was carried out partly in response to the Chernobyl nuclear disaster. A new turbine was installed in 2006, increasing the capacity to 485 MW.

The enriched uranium must be replaced after four years. It is then reprocessed once in France (recycled and re-enriched) so that it can be used for another four years. From the fission products, plutonium and uranium-236 that were created in the first four years, the fission products, which constitute nuclear waste, are removed, returned to Borssele, and stored there at COVRA.

The reactor centre in Petten is a nuclear facility near Petten (northern Netherlands) that houses a small nuclear reactor for the production of radionuclides (radioisotopes) for medical use. In addition to this high-flux reactor, a smaller low-flux reactor was in use for training purposes and materials research until 2012. Since about 2010, there have been plans to build a new reactor, PALLAS, exclusively for the production of medical isotopes.

The low flux reactor had been in use since 1960 and the high flux reactor since 1961. The low flux reactor has been decommissioned and removed. The thermal capacity of the high flux reactor (HFR) is 45 MW, that of the low flux reactor (LFR) was 30 kW. The high-flux reactor produces radioactive isotopes, among other things, which, after chemical processing in a special production facility in Petten, are supplied to hospitals for diagnostics and cancer control (radiotherapy). The reactor in Petten produces a third of the medical isotopes worldwide.

Because the current reactor is at the end of its life, there are plans for new construction. This reactor, called Pallas, is to replace the high-flux reactor before 2030.

D.3 State of the art

D.3.1 State of the art — Plants

The last NPP in the Netherlands is entering its last 10 years (Borssele).

Ideas are now being put forward in the Netherlands to build two new NPPs.

Most of the medical isotopes are made in Europe, in six nuclear reactors, one of which is located in the Netherlands (the HFR Petten). All but one of the reactors are advanced in age and sooner or later they will have to be closed. The Netherlands is considering building a new reactor named Pallas. Pallas is already in preparation and the basic design has now been completed and must be in operation before 2030.

D.3.2 State of the art — Digitization/digitalization

D.3.2.1 General

In practice, sometimes a difference is made between digitization and digitalization:

- Digitization is the process of converting information from a physical format into a digital one.
- Digitalization is the process of leveraging digitization to improve business processes.

For existing NPPs, digitization will be the most important one, however digitalization is the main focus for Pallas.

D.3.2.2 Borssele

The original designs were documented on paper drawings and descriptive reports, which have been digitized be means of text searchable scanning so the design can be searched with “Google-like capabilities”. There is a robust CM process in place which must assure up to date as-built documentation. The CM process is based on the IAEA report Modifications to Nuclear Power Plants SAFETY GUIDE No. NS-G-2.3. There is no digital CM system in use other than the document management system (DMS) which is based on Lotus Notes.

There are several propriety databases in use for the management of, e.g. pipes and temperature transients over the lifecycle of the plant.

D.3.2.3 Pallas

Pallas endorses the state of art regarding digitalization of existing NPPs as described in the report IAEA TECDOC-1919[41]:

"Nuclear power plants use multiple information systems and databases from different vendors for different purposes. Most of these systems are not integrated with one another and cannot easily share plant data during different phases of the nuclear power plant life cycle, such as design, operation and decommissioning. This results in redundancies in capturing, handling, transferring, maintaining and preserving plant data. This lack of interoperability stems from the fragmented nature of the industry, paper-based document control systems, a lack of standardization and inconsistent technology adoption among stakeholders."

Derived from the business model of Pallas they have the following vision on asset management and digitalization:

- Pallas management has a responsibility to effectively and efficiently manage the services provided by its assets, to its (medical oriented) community.
- Pallas has a strong vision for the future of asset management which includes sustainable and flexible services delivery, community satisfaction, sustainable financial position and acceptable risk exposure.
- Therefore, Pallas opts for an integrated, innovative systemic, integrated approach for the services provided by Pallas to their customers (being a service system) and the product system, being the Pallas reactor, which is utilized as such in the service system. A third system to be integrated is the Pallas organisation itself, being an enterprise system.
- In a strategic asset management plan (SAMP) Pallas provides key stakeholders with a view of how Pallas wants to integrate all three aforementioned systems (product system, service system and enterprise system) and be able to be responsive to changing requirements and future trends. With integration Pallas means traceable coherence between the Why, How and What of all three systems.

Thus, effective asset management requires a long-term, integrated view on several topics which may historically have been seen in isolation:

- maintenance and inspections;
- surveillance and periodic testing;
- management of ageing and obsolescence;
- performance monitoring and feedback of operating experience;
- management of modifications;
- preparation for decommissioning;
- assurance of delivery of product to customers as agreed with them;
- assurance of delivery of the quality as agreed with customers.

D.4 Gap analysis

For the gap analysis, i.e. the gap between today's state of the art and the visionary state as explained above, Pallas refers to the following fragments taken from the IAEA TECDOC-1919[41] (between “”) with some additional remarks.

“It is essential to maintain and ensure the integrity and validity of design basis knowledge and information over time to support the safe and efficient operation of NPPs, support effective decision-making and mitigate the risk of knowledge and information loss”.

Decision making in this context concerns decisions on technical plant level and business processes as well. This covers not only design basis knowledge but also the engineering and physical construction of the plant (referring to the IAEA equilibrium triangle).

“New NPPs can be delivered with an advanced computer-based plant information environment that is comprehensive, detailed and able to be integrated and interoperable with the information systems of the operating organization. The primary challenge with these advanced computer-based plant information environments is that they typically consist of one or more PIMs that are interfaced for information exchanges with a limited level of information interoperability among them.

These advanced computer technologies provide an opportunity to radically improve knowledge, information and data capture, integration, sharing, transfer and use between stakeholders if industry-wide standards and good practices are adopted and knowledge-centric information frameworks are developed, incorporated and widely used.

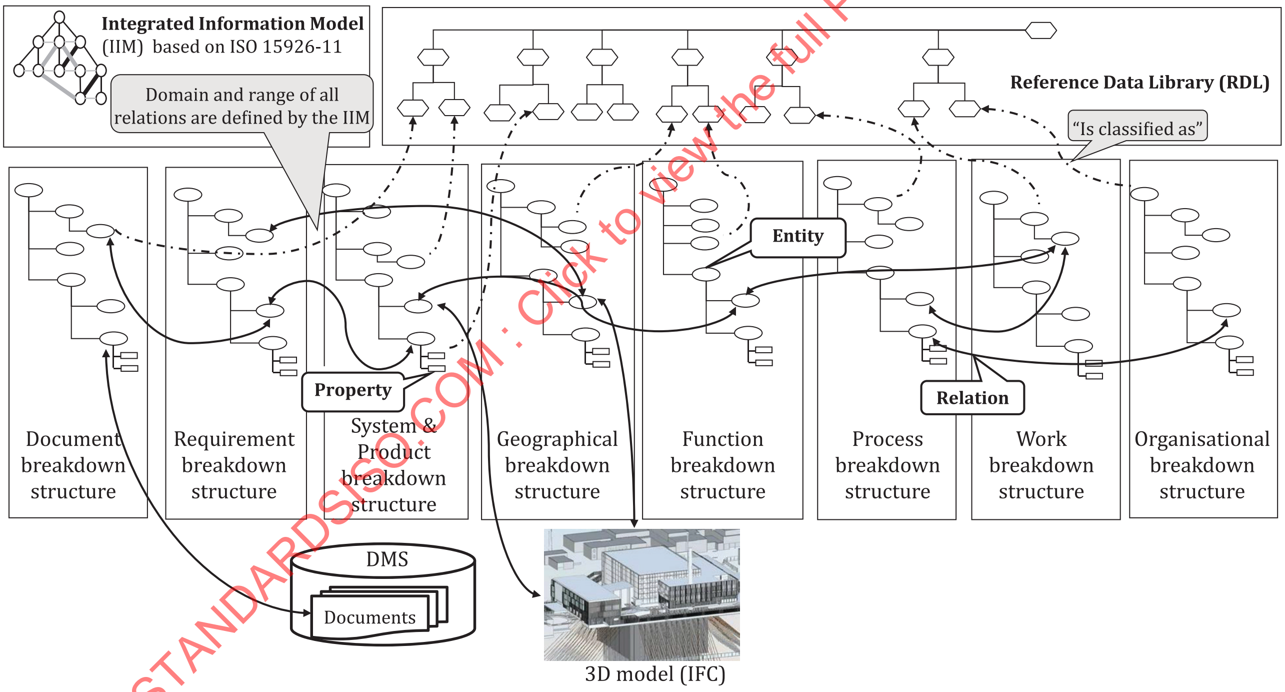
A K-PIM could be developed and leveraged as a modern and efficient approach to better support, manage and enable seamless sharing, transfer and use of sustainable nuclear design knowledge and information within and across all NPP life cycle phases".

Pallas would like to extend the K-PIM with the management and business processes relevant for operating the plant and delivering their services to the clients.

D.5 Recent significant achievements of the Pallas project

During the basic design, Pallas developed an abstract semantic layer c.q. information model that covers the needs to describe the Pallas reactor for all disciplines and all life cycles. In parallel an RDL has been developed, which will be further enriched during the progress of the project. Both are based on the ISO 19650 series, ISO/TS 15926-11 and the Dutch NTA 8035. The biggest challenge was to capture and integrate the output data of the various engineering tools in use on the EPC side of the project where even within the same discipline various tools are being used, all with their own core model and export functionality (see D.3 state of the art).

Therefore, main breakdown structures were defined in a CDE, described in ISO 19650-1, and which are the placeholders (so called master data) for all kinds of relevant design information by using semantic relationships as defined in ISO/TS 15926-11. This is shown in Figure D.1 below.



Key

⬭	breakdown structure element (instance of an Integrated Information model entity)
⟷	defined association between breakdown structure elements
-·-·-→	classification of breakdown structure elements as an RDL class

Figure D.1 — Main breakdown structure in the Pallas project

In this approach Pallas accepts that within the engineering process use is made of all kinds of engineering software tools that the engineering disciplines are familiar with in order not to disturb their process. However, by means of information delivery requirements with respect to the output of the relevant engineering software tools the structure and content of the data is managed and fed into a cleaning process for harmonizing with an integrated information model and mapping all entities to the RDL.

The result from the cleaning process is imported into the CDE in which all data is organised and integrated around the breakdown structures. The content of the CDE is exported as a turtle file (containing actual data and the history of changes) into a graph database on Pallas side, which functions as an interface to a conventional PLM system in which the data from the CDE is combined with 3D IFC files and documents based on references (URI's). This is represented by Figure D.2.

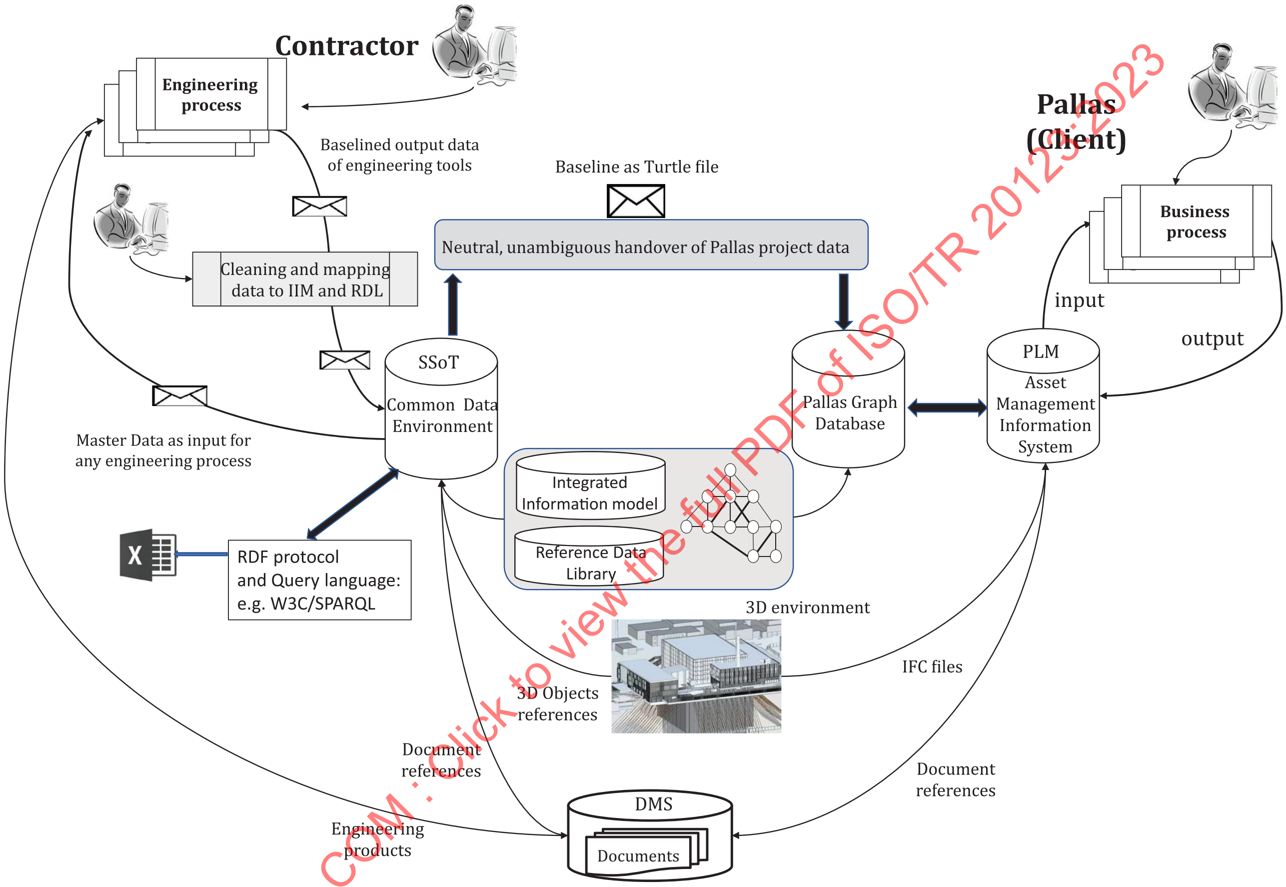


Figure D.2 — Digital ecosystem as in development at the Pallas project

This approach of Pallas is in line with the following fragments taken from the IAEA TECDOC-1919[41] (Between "") with some additional remarks.

"Concepts are the basic building blocks for modelling a domain of knowledge. Such a model is generically referred to as knowledge organization system (KOS). It includes a broad range of term lists, taxonomies, thesauri and ontologies. KOSs vary in functional purpose and semantic expressivity. Standardization of KOSs by the World Web Consortium (W3C) standards allows its full power to be exploited by interlinking and utilizing them to build comprehensive knowledge networks which form the foundation for developing knowledge-based applications."

A common language may be specified as a vocabulary or a thesaurus, containing all the concepts describing a given knowledge area. The simple knowledge organization system (SKOS) standard is well suited to formalize the vocabulary, structuring it in a hierarchical way by broader/narrower relationships, and adding attributes such as definitions, examples and notes.

For the development of the knowledge model, existing ontologies can be reused. Such ontologies may exist within the organization or be taken from external sources such as the RDL defined for the process industry in the ISO 15926 series.

Finally, the ontology will be populated with instances. All instances of a class inherit the attributes and relations assigned to the concept. For example, the concept “Pump” may contain the attributes “component ID” and “nominal flow rate”. A possible sub-concept might be defined as “Feedwater pump”, which inherits the attribute definitions of “Pump”. A specific feedwater pump might then be assigned to the concept of “Feedwater pump”, which specifies its component ID and the numerical value of flow rate. The integral of ontology and instances constitutes the knowledge base for the domain.

Other relevant supporting International Standards are:

- The ISO 8000 series describes the features and defines the requirements for the data quality and portability of enterprise master data. This standard is similar to ISO 9001 which defines the quality rules and processes for management of the quality of documents.
- ISO 14721 defines the reference model for an open archival information system (OAIS) in order to preserve information over time.

Reference data in the construction and oil & gas industries:

This generic reference data is particularly important to raise awareness of stakeholders and to support them in the implementation of a common language for information and knowledge sharing. Reference data can take the form of taxonomies or ontologies with specific scopes of coverage, such as sources of reference data and relationships models proposed in the following International Standards:

- ISO/TS 15926-3 specifies an RDL for geometry and topology.
- ISO/TS 15926-4 contains an initial set of RDL for physical objects, activities, properties and other reference data necessary to record information about process plants and oil and gas production facilities. It contains definitions as well as classification relationships between reference data items.
- ISO/TS 15926-11 define an initial set of relationships to support integration of systems engineering principles. Those relationships can model:
  - systems engineering statements such as the breakdown structures composition or the formalization of requirements, interfaces or risks applicable to an item.
  - metadata about the system engineering statements that describe traceability, maturity, status of information or rationale for design changes.
- ISO/TS 15926-11 supports full traceability of the history of a Configuration Item with block-chain characteristics. This includes the availability of meta data concerning accessibility and security for users of the data, to be interpreted by software. Also exchange of data exchange files can take place fully encrypted.

W3C has published the RDF standard that formalizes “triples”. A triple is a linking structure that forms a directed, labelled graph, where the edges represent the named link between two resources represented by the graph nodes. Each element of the triple is uniquely identified through a unique reference identifier (URI). See Figure D.3 and Figure D.4.

A named graph is key concept of semantic web architecture in which a set of triples is identified using a unique URI and that can contain metadata about those triples.

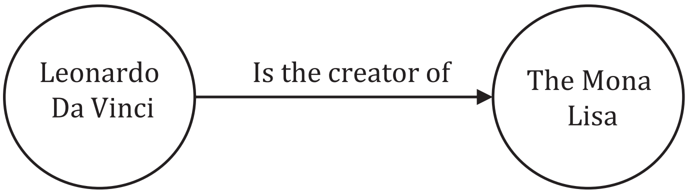


Figure D.3 — Illustration of the RDF triple concept

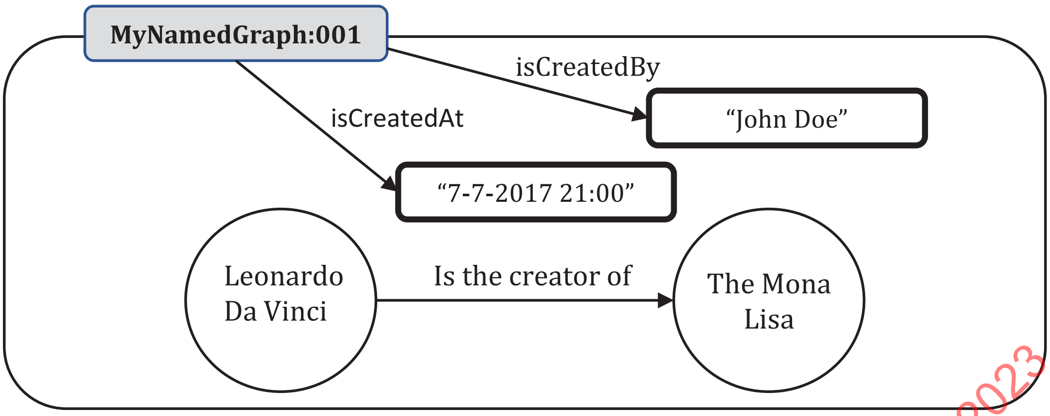


Figure D.4 — Illustration of the named graph concept

Finally, the relationships defined above about ISO/TS 15926-11 relate to the need for design knowledge rationale and traceability in a K-PIM. These relationships can be used as a foundation for the development of a knowledge-centric model that would enable management of knowledge throughout the life cycle of an NPP.

D.6 Mid-to-long term view Pallas

For the mid-to-long term view, Pallas refers to the following statement taken from the IAEA TECDOC-1919[41] (Between “”).

“In scenario three described in the IAEA TECDOC-1919, the PIM is represented in a stand-alone, custom-developed information model based on metadata semantics and modelling of business processes. Once the PIM is represented, the software that can best support it may then be identified. In this scenario, the PIM is semantically organized and structured into separate layers consisting of an item/data lexicon, an abstracted model layer that describes the information with relationships, rules, knowledge, objects, attributes, etc., and represented and managed within the systems and processes of an organization.

This is the most theoretical and idealistic among the three scenarios, as currently there is no industry standard or best practice that is mature enough, or even knowledge-centric enough, to fully represent this enhanced PIM concept. This is, therefore, the one scenario that in fact justifies the need for the development of a K-PIM that could then be used when purchasing or developing IT systems. The K-PIM is described more fully in Section 3, but the K-PIM would provide the semantically enhanced and organized foundational inter-operability infrastructure, knowledge-centric framework and common language for the seamless exchange and transfer of sustainable design knowledge information across the NPP life cycle in a more useful way: understandable, logical, traceable, reproducible and manageable. The major software and solution vendors will, in the near future, adopt the concept and support development of a K-PIM, and integrate it into more commercial off-the-shelf (COTS) IT systems that would then automatically be interoperable with other IT systems developed or purchased during the lifetime of the plant. This would, in turn, make the process of selecting and implementing PIM-based IT systems and software applications for the new NPP easier and more effective.

This section will explain how the implementation of PIMs is of central importance in the design and knowledge management (DKM) process. DKM addresses the complex initial design process for NPPs and maintaining and revising this information and knowledge over time (i.e. throughout construction, commissioning, operation, modifications, and decommissioning). The application of DKM spans organizational boundaries, as, over a plant’s life cycle many stakeholder organizations typically either contribute to the design of an NPP or are users of design information in order to carry out their works (e.g. plant maintenance and outage support).

Effective DKM will ensure retention, availability and consistency between the initial design, licensing basis requirements, physical configuration, modernization of plant components and accumulated operating experience that are essential to the maintenance of design basis and CM. The design knowledge should be accessible and available to support plant safety throughout the NPP life cycle. However, effective DKM might not be realistically happening yet because of the existing organizational, technical, legal and other barriers hampering design knowledge capture, verification, integration, transfer and modification over the life cycle.

To manage the design change process, information from all relevant disciplines is needed to support the design basis and other requirements of NPPs. In the past, such information was frequently stored in isolated databases and made effective collaboration difficult. The use of a common data dictionary providing a singular, unique definition of data concepts across disciplines, can bring consistency to these databases. In addition, a common dictionary can support data and information exchange with business partners and suppliers by using a semantic framework.

CM can be achieved in a number of different ways. However, one of the most effective ways of doing this is to utilize a PIM framework as the basis for the NPP information infrastructure. This is mainly because of the ability of the PIM to serve as a "single source of truth" to identify the relationships, status and version of SSC documents, and their corresponding design and licensing basis. This forms the key essentials of the CM "triangle" and verifies equilibrium. Such a capability depends primarily on a reliable database model that may be accessed easily and can interface and interoperate with other information utilized for the NPP.

A K-PIM is a semantically organized set of information describing plant structures, systems and components, incorporating relationships and rules within a knowledge framework that collectively forms enriched representations of the plant that provide shared knowledge services and resources over its life cycle. Consequently, a K-PIM may be a PIM, enriched with knowledge resources that incorporate semantics and knowledge services over the whole life cycle of a plant

K-PIM is a modern information technology solution with a knowledge-centric interoperability infrastructure and framework underpinning successful DKM within and transfer across all NPP life cycle phases

The concept of a knowledge-centric PIM creates numerous benefits and business drivers, as presented in this document. It provides a strong technical and managerial case for industry development of a comprehensive K-PIM. The K-PIM is the evolutionary solution to providing the industry with a practical, standardized and portable information and knowledge repository, providing the common knowledge infrastructure that provides for understanding and sharing of critical nuclear experience.

PIM in the form of an engineering data management system is the core for creating an integrated foundation for making process-related, engineering and management decisions during plant operation and decommissioning. Data consolidation in a single information storage increases efficiency and ensures transparency and safety of plant operation".

Annex E
(informative)

Nuclear power in the Republic of Korea

E.1 Background

E.1.1 Status of nuclear power plants (NPPs)

As of 2019 in the Republic of Korea, 24 reactors are in operation, where 21 of the plants are using PWRs and three are using pressurized heavy water reactors. Four reactors are under construction using the reactor model of APR 1400 (PWR). No plant is under the decommissioning process.[33]

Two plants have been shut down. Finally, there are 11 NPPs of which operation licenses will expire by 2030.

Owner operator in the nuclear power sector in Korea is:

- KHNP: Korea Hydro & Nuclear Power Co. Ltd.

Major nuclear types are:

- PWR / WHF, OPR-1000, France CPI, France CPI, APR-1400
- PHWR / CANDU6

E.1.2 Status of nuclear power plant (NPP) domain facilities (waste)

Issues regarding the decommissioning and waste disposal of NPPs are continuously being discussed.

At present, the spent fuel from PWRs has been stored temporarily in storage pools at the power plant site, while those from the pressurized heavy water reactors are stored in storage pools and dry storage (concrete canister) at the power plant sites. NPPs currently in operation are equipped with gaseous, liquid, and solid waste treatment facilities and on-site storage facilities to ensure the safe management of radioactive waste generated in the operation process. The on-site solid radioactive waste storage facility is a concrete slab type building with separate storage for waste according to the radioactivity level and is equipped with a radiation monitoring system.

The nuclear waste from research facilities and fuel fabrication facilities is stored in a separate waste storage facility managed by the Republic of Korea Electric Power Company (KEPCO) isolated from the NPP waste.

E.2 State of the art for nuclear power plant (NPP) standards

Public companies mainly lead the nuclear power industry in Republic of Korea, and the number of companies participating is minimal. A major equipment supplier has been privatized; a limited pool of private general contractors is joining for construction.

The entire project has been carried out according to the standards developed by a public company that is a public owner-operator organization. However, these standards are not registered as a Republic of Korean Standard (KS). Accordingly, there are efforts to systematize the current standards at the national level.