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

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National foreword

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TECHNICAL REPORT

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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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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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

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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.

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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]

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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]

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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 service*s* 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.

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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

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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

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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

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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]:

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

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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.

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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.

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

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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

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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

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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.

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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);

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— 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.

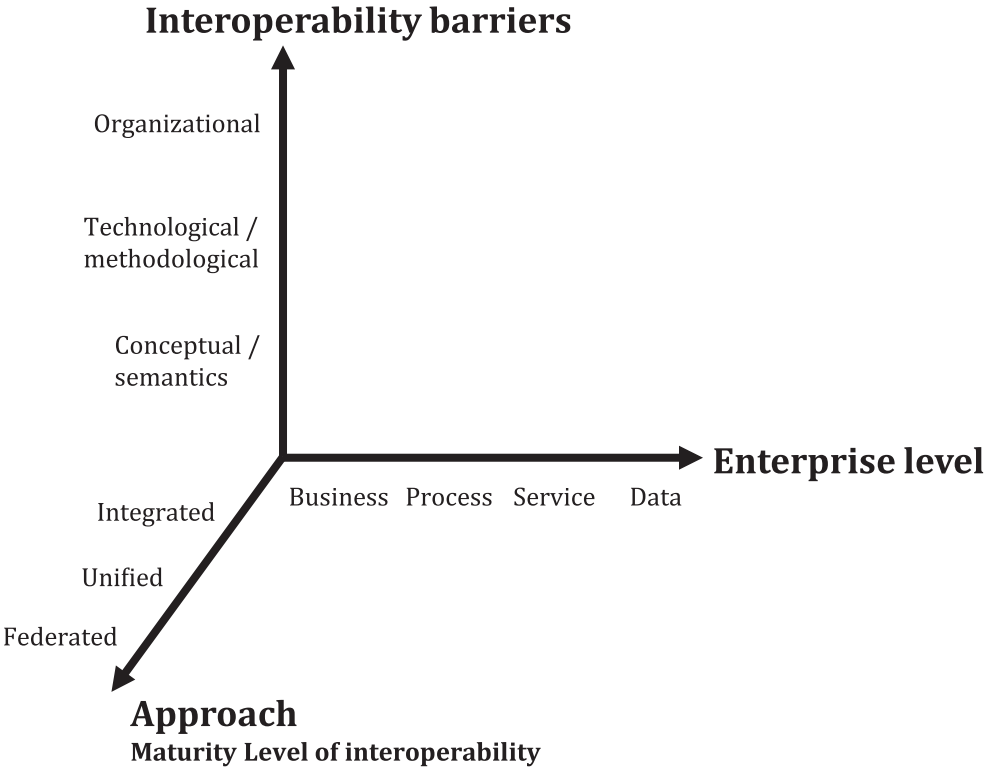

Figure 1 — Interoperability barriers – Enterprise level matrix to position a certain interoperability issue (based on ISO 11354-1)

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.

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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

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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.

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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.

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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.

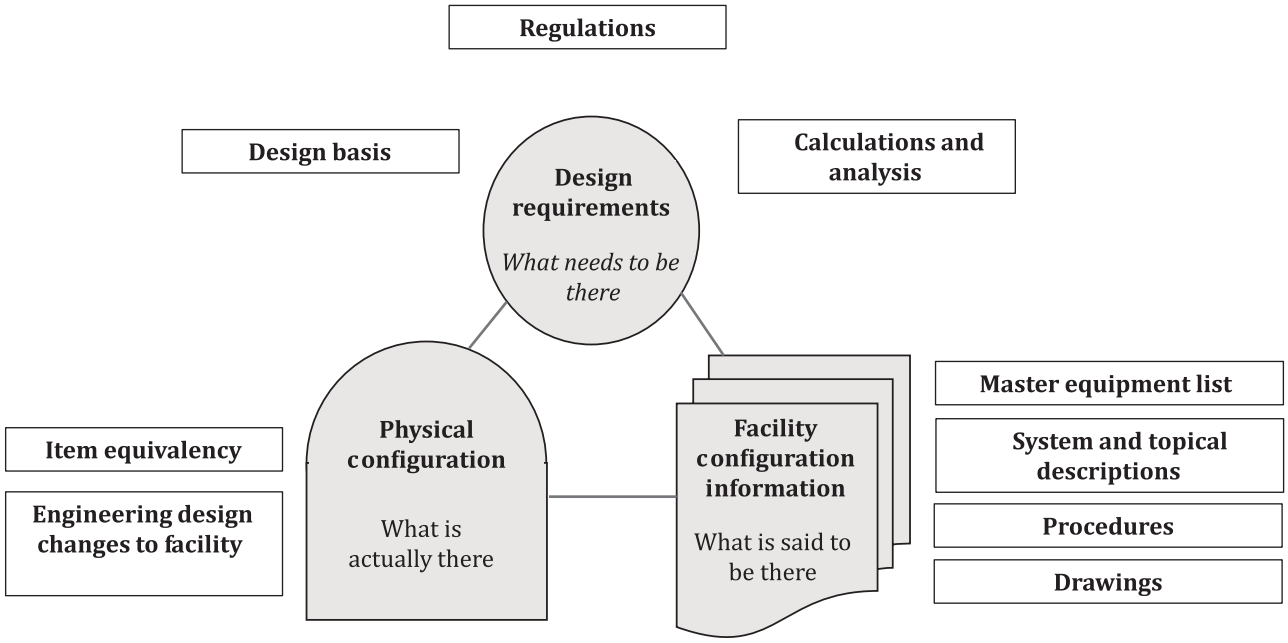

Figure 2 — Configuration management (CM) of a nuclear power plant

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

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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.

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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.

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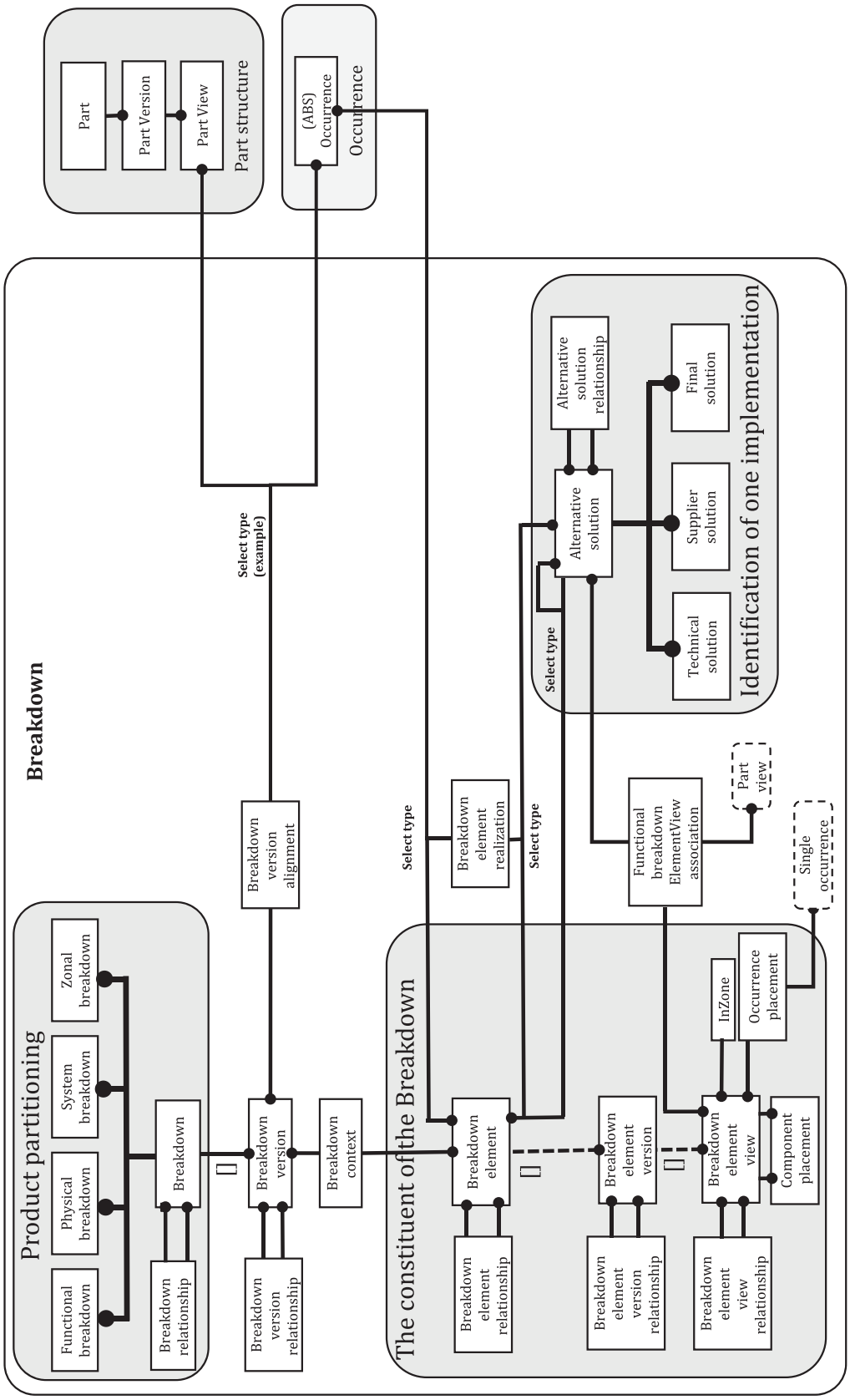

Figure 3 — Information model to illustrate the concept of breakdown

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

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