Japan-Germany Standardisation Expert Meeting

Advancing Semantic Interoperability Layer as an enabler for AI-driven Manufacturing Transformation

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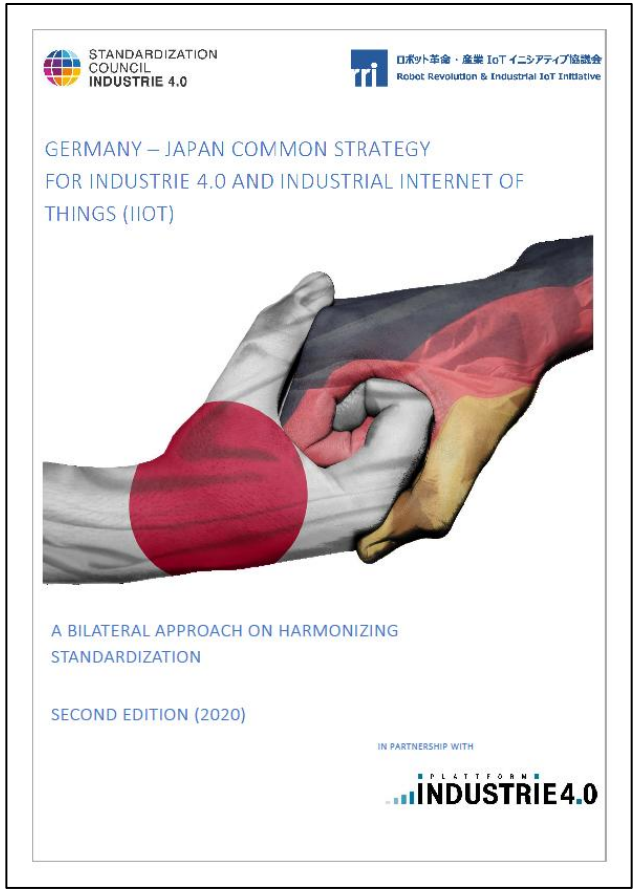
0. Overview of Germany - Japan collaboration

In 2016, Robot Revolution & Industrial IoT Initiative (Japan) and Plattform Industrie 4.0 (Germany) have agreed to cooperate on standardization in the field of smart manufacturing.

IIoT/Industry 4.0 requires an unprecedented degree of system integration across domain borders, hierarchy borders and life cycle phases.

It is critical to consider the standardization as a basis for open and interoperable system architecture for industrial implementation of the vision of Smart Manufacturing.*

This presentation is based on the Germany – Japan collaboration for advancing semantic interoperability In smart manufacturing.



*: Germany – Japan common strategy for industrie 4.0 and industrial internet of things (IIOT) (https://www.jmfrri.gr.jp/document/library/1650.html)

1. Introduction: Background (Overall Journey of Semantics)

Taxonomy
Classification, Semantics and Type Hierarchy

- Sensor: Temperature Sensor, Pressure Sensor, …
- Actuator: Valve, Motor, …

defined in **CDD** **EClass**

Information Model + Property Definition
Properties, Relations and Shared Meaning

- Injection Molding Machine has Temperature Sensor
- Temperature Sensor has Device Nameplate
- Temperature Sensor shows internal temperature in Celsius

uses **CDD** **EClass**

defined by **OPC UA CS** **SM Profile** **AAS SMT**

Practical Use Cases

- Temperature can be analyzed for Quality Assurance
- Temperature value indicates necessary actions in the sense of predictive maintenance

uses **CDD** **EClass**

uses **OPC UA CS** **SM Profile** **AAS SMT**

done as **Interoperable Implementations**

Type Definition

Instance

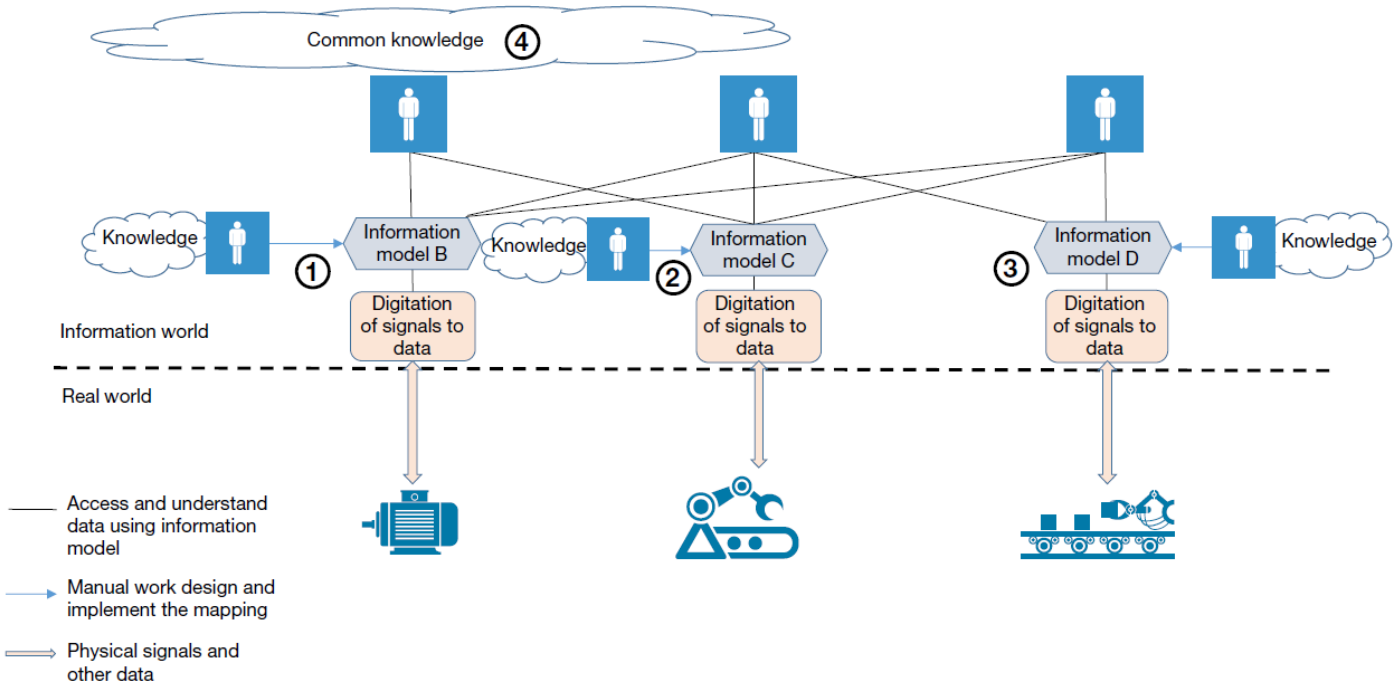
1. Introduction: Background

Cross-domain data exchange becomes increasingly important in smart manufacturing.

Ontologies for information models play an essential role for semantic information sharing.

However issues of comprehensive semantic information sharing in dynamically evolving industrial environment are not well recognized and understood.

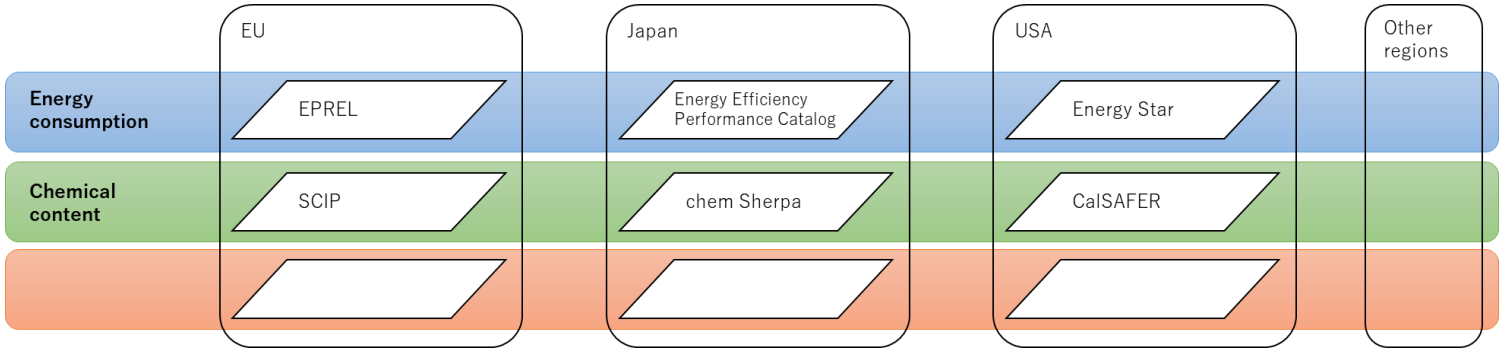
Different concepts based on different knowledge result in different information models *



*: IEC White paper: Semantic interoperability: challenges in the digital transformation age, 2019.

1. Introduction: Background

Semantic information sharing in dynamically evolving industrial environment in different regions



Can we establish a global single point of truth for globally interoperable data ecosystems?

X, Y …Z

Collection of data points for application specific Use Cases → e.g. as submodel template for AAS

X+a,b,c

Country A

Country (region) specific legal requirements for DPP-Data

…

X+m,n

Country N

Country (region) specific legal requirements for DPP-Data

International standardized semantics for unambiguous description of data points.
This could be done at

- recognized standardization bodies → IEC + ISO CDD
- consortia → e.g. ECLASS

International standards describing requirements on the technological base layer (system). E.g.:

- IEC 63278-series on AAS
- IEC 61360-1 describing information model of Common Data Dictionary (CDD)
- …

1. Introduction: Objective

Extensive works are now in progress in smart manufacturing standardization community for semantic information sharing, where semantics is often treated as static, like fixed dictionary definitions. However, in dynamic and heterogeneous industrial reality, it should be viewed as a dynamic process that evolves with new properties and functions. In smart manufacturing, enabling cross-domain information flow requires a flexible framework where multiple domain-specific dictionaries can coexist and interoperate.

For aiming to cope with the situation above, the objective of this presentation is to discuss:

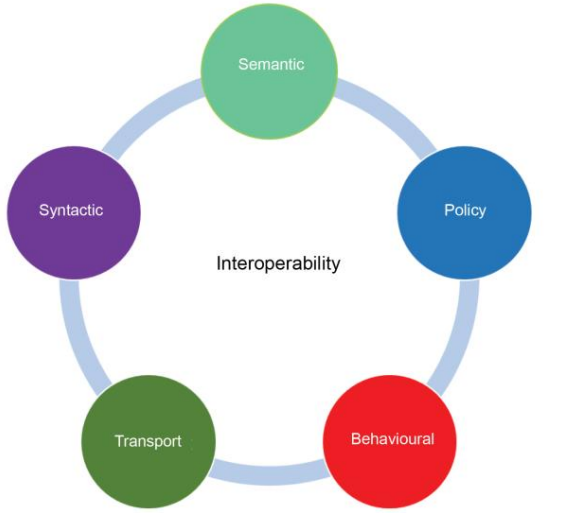
- fundamental challenges in semantic interoperability,
- proposed framework for designing toward flexibility, extensibility and coexistence,
- appropriate use of AI capabilities and governance.

2. Fundamental Challenges in Semantic Interoperability

1. Dynamic and evolving dictionaries
   - Domain diversity
   - Regional and regulatory variations
   - Continuous evolution of technologies
2. Fragmentation and growth of domain-specific dictionaries
   - Coexistence of local models
   - Convergence of technologies and IT/OT integration
   - Legacy knowledge as industrial assets
3. Standardized interoperability in processes and accessibility
   - Mapping inconsistency
   - Controlled accessibility
   - Organizational and legal hurdles

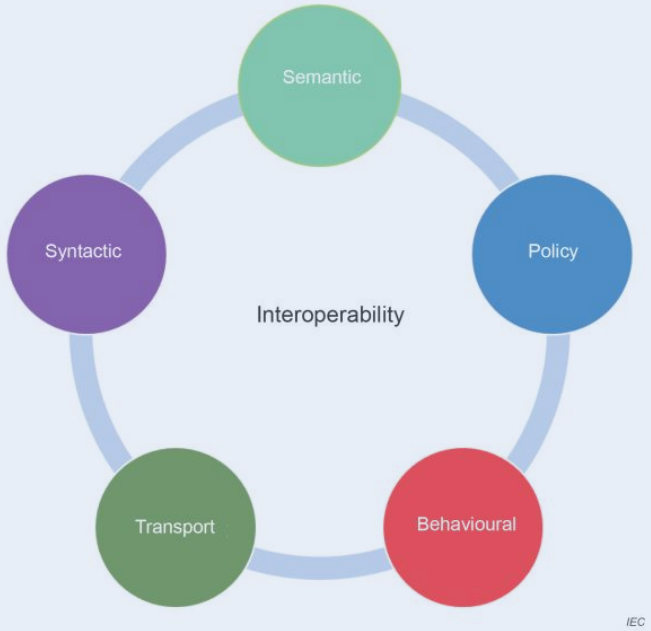
3. Proposed Framework: Designing for Flexibility, Extensibility, and Coexistence

- Defined frameworks describe different aspects of interoperability and their relations to each other
- Layered frameworks with defined interfaces are one approach to allow a migration of technologies in one layer without affecting the other layers
- Different approaches described in international standards:
    1. ISO/IEC 21823-1:2019 "Internet of things (IoT) — Interoperability for IoT systems — Part 1: Framework"
    2. IEC SRD 63417:2025-06 Guidance and plan to develop smart energy ontologies (Based on European Interoperability Framework EIF)





3. Proposed Framework: Designing for Flexibility, Extensibility, and Coexistence



Source: ISO/IEC 21823-1:2019

Semantic is focusing
on one of the main aspects of interoperability

Facets	Aim	Objects	Requirements	Examples
Transport	Data transfer between systems	Physical connections Signals	Protocols of data transfer	HTTP/S, MQTT
Syntactic	Receive data in an understood format	Data	Standardized data exchange formats	JSON, XML, ASN.1
Semantic	Receive data using an understood data information model	Programmatic interface	Common interpretation of data information model	Directories, data keys, ontologies
Behavioural	Obtain expected outcomes to interface operations	Information	Behavioural model(s) of the invoked IoT entity	UML models, pre- and post-conditions, constraint specifications
Policy	Assurance that interoperating systems follow applicable regulatory and organizational policies	Regulatory and organizational polices and interoperation context	Conditions and control for use and access	Security policies of IoT system stakeholders, restriction on cross-border data transfer, regulations controlling PII

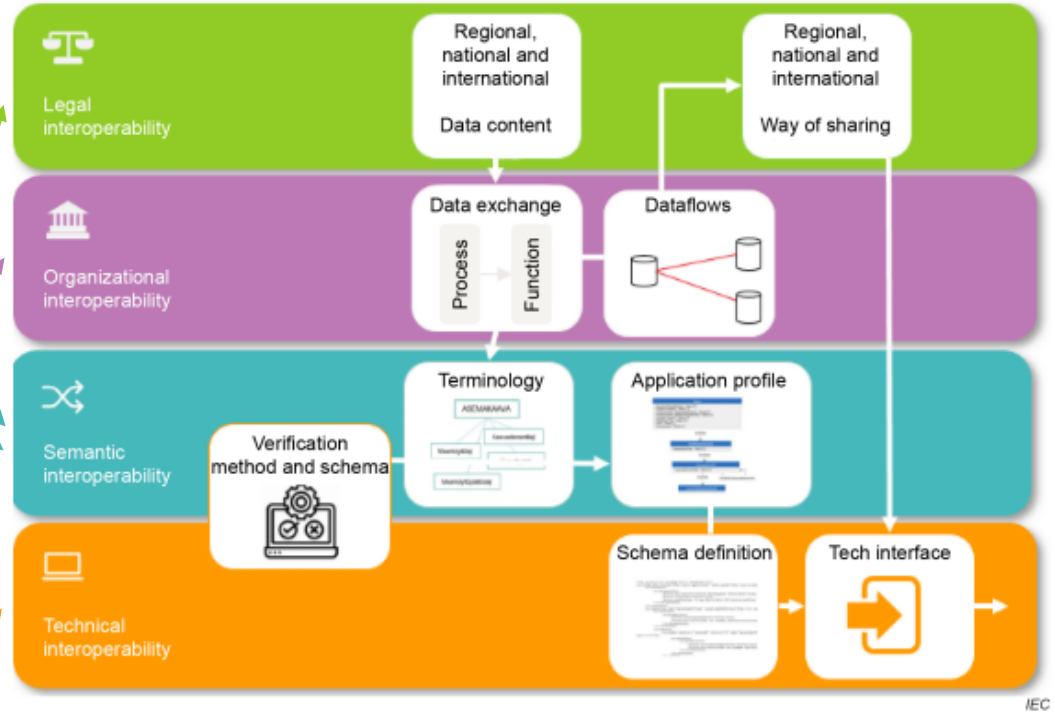
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Source: ISO/IEC 21823-1:2019

European Interoperability Framework (EIF)



Source: IEC SRD 63417:2025-06 Guidance and plan to develop smart energy ontologies / https://ec.europa.eu/isa2/eif_en/

Both standards comes from different directions: Technical view vs. Governance view

3. Semantic Interoperability Layer in Federated Data Spaces

Extensible and Modular Dictionary Architecture

Domain-specific vocabularies, modular and extensible

Federated Semantic Model

Shared meaning across organizations and data spaces

Semantic Interoperability Layer

Property Management and Versioning Strategy

Governance, lifecycle and evolution of semantic assets

Standardized Interoperability Process Model

Common processes for semantic integration and use

Enables:

- Shared Understanding
- Cross-Domain Interoperability
- Data Reuse
- Scalable Federation

→ A connected industrial future

3. Semantic Interoperability Layer: Extensible and Modular Dictionary Architecture



Extensible and Modular Dictionary Architecture

Domain-specific vocabularies, modular and extensible

Modular, extensible Integration of General and Domain Knowledge

- Modular dictionary architecture
- Reuse of multiple vocabulary with controlled namespace management
- FAIR principles for all semantic assets

  (Findable, Accessible, Interoperable, Reusable)

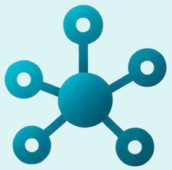
AI Perspective:

- Ensure semantic interoperability and reuse in presence of heterogeneity with respect to formats, different formal approaches to describe semantics, etc.

  → Computer-interpretable formats required, as e.g., ontologies, RDF/RDF-S, knowledge graphs, linked (open) data
- Industrial Knowledge for Physical AI: Physical AI and autonomous CPS require standardized world models to understand assets, processes, capabilities, constraints and context

  → What is the next step of dictionaries in context of industrial foundation models and World Models?

3. Semantic Interoperability Layer: Federated Semantic Model



Federated Semantic Model

Shared meaning across organizations and data spaces

Acceptance of heterogeneity, enable integration, leveraging interoperability

- Principle of Coexistence as the fundamental design principle
- Harmonization through reuse of international standards
- Standardization on meta-level for trustful mappings and semantic bridges
- Integration of industrial and regulatory initiatives (e.g., DPP, IEC CDD, ECLASS, ELI)

AI Perspective:

Industrial AI requires access to various levels and kinds of data & knowledge; recent (semantic) models are often impractical due to sovereignty, ownership and scalability constraints.

- Not flat but heterachically federated knowledge and data spaces in real industrial contexts
- Exhaustive need for „internal“ knowledge: Data & knowledge encapsulated (but not or only partially shared) internal knowledge
- missing contextual information for reliable interpretation of data by AI (beyond „just“ semantics)

→ embodied AI drastically increases need beyond existing industrial data models

3. Semantic Interoperability Layer: Property Management and Versioning Strategy



Property Management and Versioning Strategy

Governance, lifecycle and evolution of semantic assets

Trust through Governance | Managing Semantic Evolution

- Semantic assets evolve throughout their lifecycle and require controlled governance.
- Traceability, provenance and change management are prerequisites for industrial trust and regulatory compliance.

AI Perspective: What if AI is consuming data?

- Data usage and provenance:
  - What about usage control when data is delivered and consumed by AI?
    → Provenance, explainability, Transparency
  - How can we trace data usage in AI reasoning and AI tasks?
    → Traceability, Auditability and Trust
  - (Hypothetic) example: if the calculation of creepage distance is modified
    → how to re-train the AI models for design of electric systems?
- AI needs to deal trustfully with versions and (semantic) changes; deal with temporal aspects and scope

3. Semantic Interoperability Layer: Standardized Interoperability Process Modell



Standardized Interoperability Process Model

Common processes for semantic integration and use

Standardized Interoperability Process Model

- Repeatable, governed workflows for trust control
- Formalizes discovery and validation, and governance across the knowledge and data lifecycle.

AI Perspective

- AI agents increasingly participate in discovery, integration and orchestration processes.
  → New trust challenges arise when actors are autonomous technical entities (agents)
  → AI-driven interoperability requires trusted workflows rather than technical interfaces.

- Consistent governance processes are needed to validate semantic assets, mappings and AI-generated artifacts.
- Autonomous systems require machine-executable governance to ensure reliability and accountability.
- Industrial AI demands end-to-end consistency between engineering, operation and lifecycle management.

4. Summary and conclusion

Joint forces of JP and DE in core future topics:

- Semantic interoperability is a key technology for industrial AI
- Data sharing | industrial data spaces
  → Interoperability on data level | Interpretability on knowledge level
- Versioning of semantic definitions is an emerging challenge
  → AI usage adds more urgency and relevance to this aspect
- The term Industrial AI is still evolving
  - Physical AI / Embodied AI → Industrial AI meets Robotics

The white paper is available for download via the QR code.

Thank you for your attention

Danke für Ihre Aufmerksamkeit

ご清聴ありがとうございました

https://www.jmfrri.gr.jp/library-english/advancing-semantic-interoperability-layer-as-an-enabler-for-ai-driven-manufacturing-transformation/