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Interoperability standards for circular manufacturing in cyber-physical ecosystems: a survey

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Abstract

Cyber-physical ecosystems are among the most promising solutions to adopt circular manufacturing (CM), extending product lifecycles with customer-centric approaches that optimize energy and materials use in interconnected organizations. However, information sharing increases significantly, putting standardization at the top of the industry priorities. This paper reviews interoperability standards for circular manufacturing and devises initial guidelines for its identification and management in cyber-physical ecosystems. The study was conducted within the framework of KYKLOS 4.0, one of the innovative Horizon 2020 projects advancing the field. The results include (1) an overview of interoperability standards in manufacturing and (2) the proposal of a standards list to support circular practices. Our findings are relevant for identifying circularity requirements in cyber-physical ecosystems and defining an interoperability baseline. As more standards appear in the market, continuous interoperability assessment and cyber-physical structures for multi-standard scenarios must enter the manufacturers' agenda.

Keywords: Interoperability; cyber-physical ecosystems; standards; KYKLOS 4.0

1. Introduction

Interoperability is one of the essential pillars of circular manufacturing. This new paradigm aims to extend product lifecycles, reduce waste, and improve sustainability [22]. Circular manufacturing also requires a solid infrastructure for information sharing among the ecosystem actors [1]. Therefore, new opportunities emerge from adopting cyber-

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physical ecosystems [32,24] motivated by the increased flexibility in dynamic supply chain configurations, decentralized operations, and constant optimization of physical and digital assets to create customized products.

Interoperability is also foundational in the fourth industrial revolution, enabling horizontal, vertical, and end-to-end digital integration of supply chains [6]. The conventional automation layers in manufacturing (e.g., field devices, control, supervision, or planning) are expanded to a multi-site infrastructure. Therefore, the interdependencies within product lifecycles have increased drastically since the early product design stages. The benefits of a standards-based approach to interoperability requirements are twofold. First, to ensure that project partners adopt best practices in their work, reducing the risks of disruptions in the information flows. Interoperability must be planned and is a result of systematic practices [12]. For example, standards can be adopted to guide digital transformation efforts in the industry and ensure effective data sharing [32]. Second, complying with standards will ensure ecosystem growth, gradually incorporating more products and actors in the reconfigurable supply chain by sharing data of agreed data definitions.

Recent studies have merged the discourse on “[i]nteroperability, integration and cyber-physical systems” [12], identified standards for “zero defects manufacturing” [23], and proposed frameworks for circular manufacturing driven by sustainable practices [33]. Our goal is to extend these previous contributions with the following research objective: to identify key interoperability standards to support circular manufacturing in cyber-physical ecosystems. This topic is addressed by KYKLOS 4.0 [16], a Horizon 2020 (H2020) project involving 29 academic and industry partners from 14 countries. Our work is part of the collaboration framework developed for the circular manufacturing ecosystem, requiring alignment with international standards.

The rest of this paper is organized as follows. Section 2 explains our research approach. Next, Section 3 presents the results: (1) bibliometric analysis to identify recent trends and important research topics for interoperability standards in manufacturing and (2) an internal survey performed in KYKLOS 4.0. A discussion follows to identify critical dimensions for standards integrating (1) the emerging concept of circular manufacturing and (2) the decentralized cyber-physical ecosystems. Section 5 summarizes the conclusions, limitations, and future work.

2. Research approach

The identification of interoperability standards has specific recommendations. For example, [21] starts with the requirements identification and proposes an iterative assessment of each standard (e.g., scope, audience, or adoption level) or the more recent European Interoperability Framework [10]. Fig.1 presents how these contributions were integrated and extended with a bibliometric analysis and a survey.

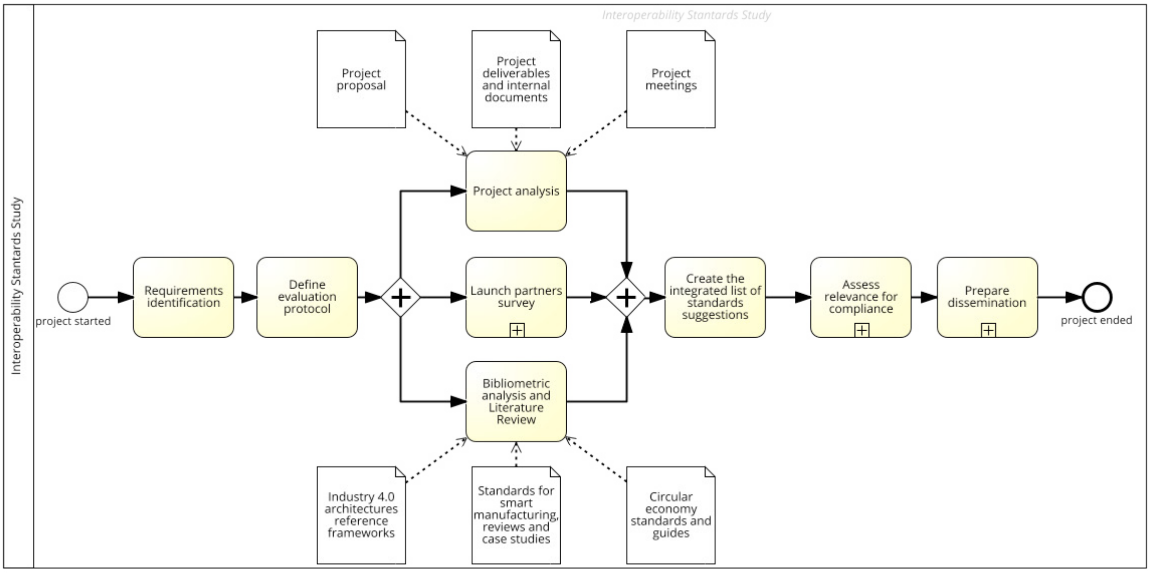

Fig. 1. Research approach

Our study started with identifying project requirements for interoperability in smart manufacturing. The need for real-time information from equipment, multiple Internet of Things (IoT) infrastructures, advanced artificial intelligence algorithms, and decision support systems to reduce waste and increase the reuse of materials within the entire manufacturing lifecycle is critical. Therefore, the team created a protocol to assess the standards aligned with (1) KYKLOS 4.0 objectives and related H2020 projects analysis, (2) a survey among project partners, and (3) a literature review based on bibliometric networks. Our approach includes a few changes when compared to earlier proposals (e.g., [21], followed in the subsequent phases of iterative standard assessment and dissemination). However, it is enhanced with the insights of bibliometric analysis. This study captures relevant concepts in a large number of papers, assisting in identifying relevant research clusters that interoperability standards should address, and identifying specific studies necessary for more detailed assessment (e.g., review of standards). Additionally, studying the current landscape of standards in KYKLOS 4.0 partners had advantages: (1) making them part of the selection process (vital for standards acceptance), and (2) identifying priorities and early warnings for incompatible standards used by different organizations in the cyber-physical ecosystem.

3. Results: Towards interoperable advanced manufacturing

The databases SCOPUS and Web of Science (WoS) were selected for the bibliometric analysis. The first goal was to identify trends in publications and citations. Second, identify relevant topics and clusters of papers. Third, compare the most relevant funding sources for standardization advances in interoperable manufacturing. Additionally, the team searched for the title and abstract to identify comprehensive studies on interoperability (e.g., [19], [5],) checked past H2020 projects with relevant interoperability requirements (e.g., [32], [19]), and evaluated recent standards suggesting catalogs, like the ISO/IEC TR 63306-2 - Smart Manufacturing Standards Map (SM2) - Part 2: Catalogue [15].

Fig. 2 presents the evolution of WoS publications and citations.

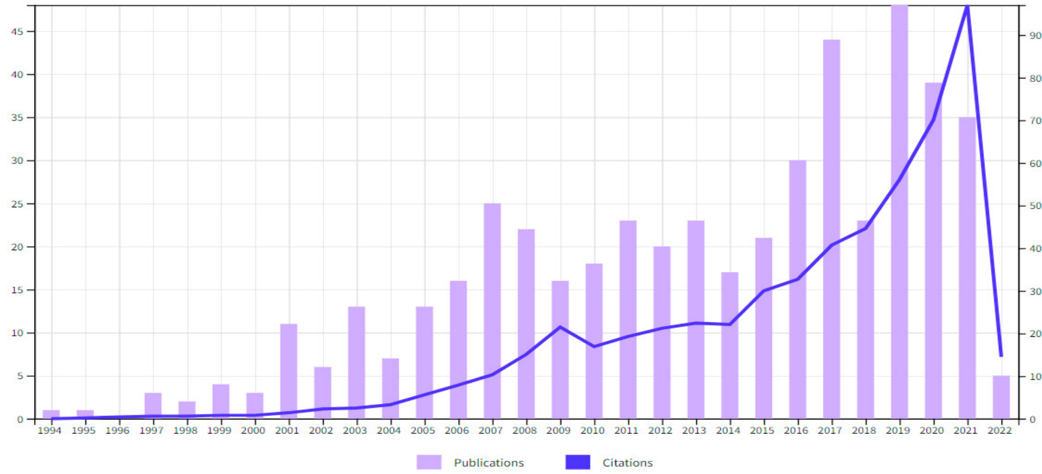

Fig. 2. Publications in Web of Science (interoperability and standard and manufacturing (All Fields))

A total of 489 publications were found in the WoS database for the selected keywords (interoperability and standard and manufacturing; last search in 04/2022), revealing 11.47 average citations per item (h-index 37). The number of papers and citations reinforces the topic's growing importance (particularly after 2013, the origin of Industry 4.0 proposals). The project team made additional searches and found surprising results. For example, the keyword combination "interoperability" and "circular economy" returned 15 papers (the majority published since 2020, reducing to 3 hits if the term "standard" is included in the search). Only a single conference paper was found for "interoperability" and "circular manufacturing", addressing enterprise information systems [26], confirming the early stages of circular manufacturing.

The WoS reveals important links with Industry 4.0 technology. For example, [2] for blockchain-enabled auditing systems, evaluation of barriers for Industry 4.0 [27], highlighting interoperability issues, and the importance of open standards [20] (e.g., IDS Reference architecture model, FIWARE open API [https://www.fiware.org/], or building-related open standards like Building Information Modelling - BIM) to share data.

Other critical studies for the scope of KYKLOS 4.0 project include the Semantic Web Rule Language (SWRL) ontology for product-service systems lifecycle [13] and advances in standards-compliant manufacturing systems adopting ISO 14649/ISO 10303-238 (STEP-NC) and IEC 61499 function blocks [8]. One of the most recent papers on circular manufacturing states undoubtedly that "[w]ithout a clear and standardized conceptualization of CE [Circular Economy] among organisations, it is difficult to implement CE practices" [7], suggesting that standards are crucial to the creation of operational strategies capabilities. Fig. 3 presents the bibliometric network created with VOS Viewer tool [9] for the 489 papers (selection on 04/2022).

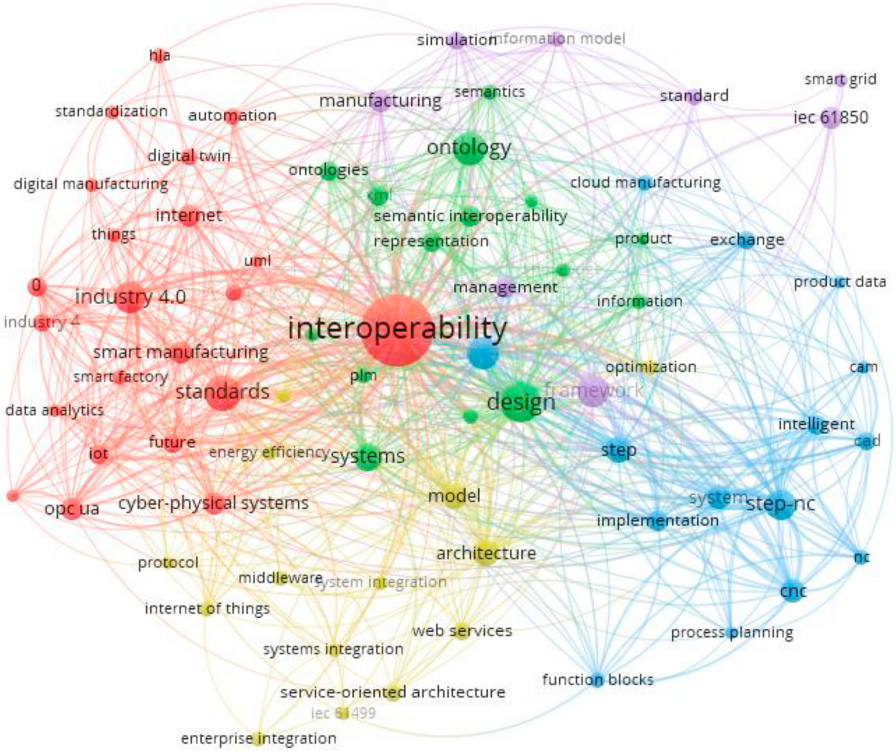

Fig. 3. Bibliometric analysis in WoS (co-occurrence of words, minimum five occurrences, cluster size 1)

Semantic interoperability and related ontologies are represented in the green cluster. Below, the yellow cluster includes models, architectures, and standards (IEC 61499) for interoperability (e.g., SOA) and, on the right, the blue cluster shows papers focusing on product information (STEP standard [18] reveals representative nodes – the size of the node is proportional to the number of papers). Finally, the red and the purple clusters include relevant standards: the red Industry 4.0-related cluster includes OPC-UA, while the purple set of papers points to the IEC 61850 (communication in substations) close to the smart grid line of research.

The USA leads the number of publications (119) and citations (1509). Three European countries follow in the list, namely, England, France, and Germany (nearly 45 papers each). China appears very close, with 43 papers and a significant number of citations (707). The analysis of the papers proves the global interest in interoperability standardization. SCOPUS shows similar results, but a more significant number of publications (614 using the same keyword) are indexed. This database is also helpful in identifying the key funding sponsors presented in Fig. 4.

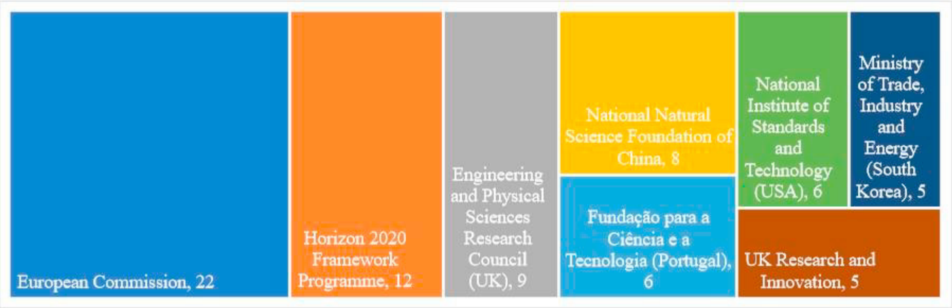

Fig. 4. SCOPUS publications in manufacturing interoperability standards – funding sponsors

The European Commission and H2020 programme, with 22 and 12 documents, respectively, are top funders in the SCOPUS list, followed by the UK and China.

Modeling tools and methodologies are required for interoperability development. SCOPUS includes some studies focusing on standardization analysis in this area. An example of a recent study addressing interoperability modeling can be found in [34]. These authors identify fifty-four standards published by different institutions (e.g., ISO, ANSI, IEC, ASME, SISO, and NIST). The study also reveals over 120 languages like UML (ISO/IEC 19501); OWL, and SWRL for knowledge representation – the "most popular way to create rules" [11]; Metamodels like AutomationML [3]; and domain-specific languages. Business Process Model and Notation (BPMN, ISO/IEC 19510) and ISO/IEC 42010 for architecture descriptions are necessary for software engineering teams. STEP (ISO 10303) is also mentioned as a vital product data standard. Examples of domain-specific standards comprise ISO 15926 for integrating lifecycle data for process plants, including oil and gas production facilities, the IEC 62264 for enterprise control system integration (based on ANSI / ISA 95), and STEP-NC (ISO 14649 and ISO 10303-238) for numerical controllers.

The results in Google Scholar are more extensive for the keyword "interoperability" + "circular manufacturing", indexing seven results in 2022. Recent evidence suggests "that the successful integration of the IoT in the CE is challenging due to the IoT's current interoperability issues, obsolescence of IoT-embedded products over time, and privacy and security concerns" [29] and confirms that "for larger, open systems, standardization is required to enable interoperability, which calls for expertise in semantics, ontologies, and data protocols" [17]. Examples of standards presented in [26] are ISO 10303, IEC 62264, or ISO 15926 for asset planning ontology (already identified in our analysis) and specific standards for condition monitoring.

The research team conducted an internal survey to identify relevant standards and the purpose of using them in KYKLOS 4.0. The results are summarized in Fig. 5.

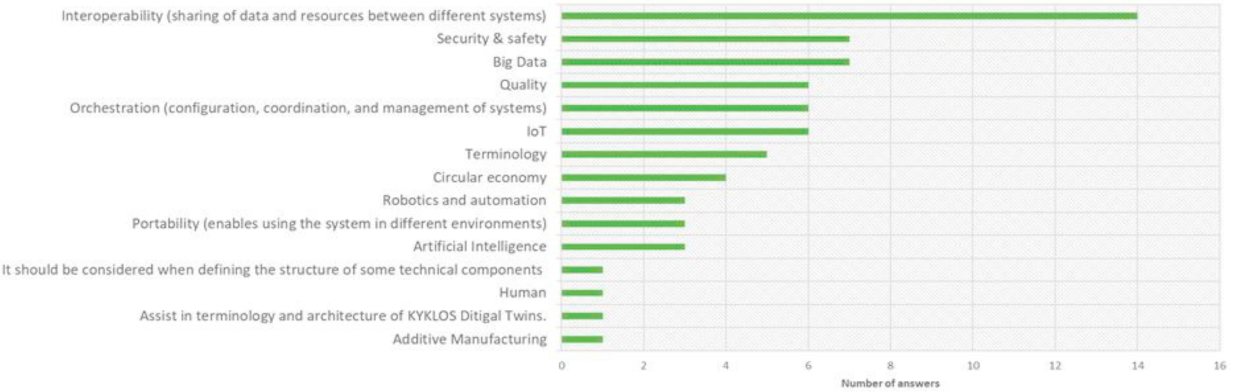

Fig. 5. KYKLOS 4.0 survey of standards - summary

The majority pointed to interoperability standards (topmost bar). For example, open standards like the OneM2M [25], sector-specific standards (e.g., ISO 14971:2019), data exchange formats (e.g., HDF5), or more high-level security standards like ISO 27001 for information security management systems. Platform-independent standards important for circular manufacturing are OPC-UA and open digital twins. Nevertheless, the team also identified more general standards (e.g., ISO 9001), IoT specifications, data-related documents, and terminology specifications. The survey uncovered the current efforts in artificial intelligence certification (countries like Germany already created their roadmaps) and the need to closely monitor technical committees' work.

4. Discussion

Standards for interoperability in circular manufacturing include more mature references and newer proposals that deserve particular attention in the following years. Digital twins and artificial intelligence are examples of the latter. This evidence strengthened our conviction that compliance with international standards should be managed in the cyber-physical ecosystem as a "process" of continuous evaluation, sharing, and tuning project components. Moreover, it is essential to consider changes during the cyber-physical ecosystem development and operation since different standards are under development and may provide improvement opportunities for circular manufacturing addressing mass customization. The solution is to create a methodologic approach to interoperability assessment.

Several frameworks have identified interoperability dimensions (e.g., [10,4]). One of the most recent studies on the topic of BIM highlights several factors organized in four main dimensions [30]: legal (e.g., regulations), technical (e.g., data integration, security), organizational (e.g., management support, financial), and semantic (e.g., dictionaries, definitions). The extensive review presented by [14] for the Industrial IoT also includes standards (e.g., HTTP, OPC-UA, RFID, OWL, MQTT), expanding the knowledge of technologies relevant to smart manufacturing. Future research opportunities suggested by these authors include examples interesting to KYKLOS 4.0, such as energy-efficient hardware, overcoming the current limitations in some standards (e.g., REST scalability, MTTT interoperable data formats), cross-domain interoperability, or security, among others [14]. These important examples reveal that it is possible to adapt interoperability dimensions [30] to specific contexts like the circular economy and emphasize the significance of identifying a combination of standards suitable for interoperability between cyber-physical ecosystems.

Standardizing data sharing in circular manufacturing also aims to prevent vulnerabilities in multiple layers (e.g., IoT, software), ensures service level verification, and provides audit trails to ecosystem participants and third-party organizations (e.g., regulators and assessors). KYKLOS 4.0 relies upon a blockchain audit solution accessible to different experts [28]. A REST API was created for interoperability purposes, making the audit trail available for mass adoption with specific rules integrated into smart contracts. The high number of devices (e.g., sensors, machines, products), circularity data (e.g., product recycling, repair), and constantly changing ecosystem participants (e.g., new companies entering/leaving the cyber-physical ecosystem depending on the product tailored to each customer) suggests that interoperability is also a foundation for scalability and evidence of compliance.

Our team adopted the popular Plan-Do-Check-Act (PDCA) cycle [31] to suggest six interrelated dimensions that interoperability standards selection must consider. First, (P-Plan) defining the *Architecture* requires a common description language. ArchiMate and OWL are good examples of standards available for this stage, well represented in the yellow and green clusters in Fig. 2. Second, (D-Do) *Sustainability* (e.g., circular practices, sustainability goals, KPIs), *Security*, and *Data Exchange* are three critical dimensions for interoperability execution. Several standards are available to guide resource optimization during the entire product lifecycle that must be implemented to ensure that manufacturing is effectively "circular". Moreover, security is a primary concern in increasingly digital and interdependent organizations. The Data Exchange dimension integrates the application, technology, and data representation (e.g., STEP represented in the blue cluster, OPC-UA in the red cluster in Fig. 2). Third, (C-Check) circular manufacturing requires continuous monitoring and assessment. The dimensions of *Intelligence* (e.g., prediction models, simulation), and *Compliance* (e.g., audit practices, reference guides) complete the inventory to enable continuous improvement (A-Act).

Although far from being exhaustive, the six dimensions extracted from our bibliometric networks and the previous studies on the topic highlight the need to continuously improve interoperability and the need to balance the most immediate standardization requirements (D) for data formats or data exchange protocols found in the literature with the planning (P) and evaluation (C) standards available. Therefore, KYKLOS 4.0 analysis included at least one interoperability standard for each dimension, guiding designers and project assessors in their tasks.

Appendix A presents relevant standards for “smart” circular manufacturing, summarizing the integration of the literature review (scientific and related projects) and the survey with companies, according to the six dimensions.

5. Conclusion

This paper presented a bibliometric analysis of interoperability standards incorporating circular manufacturing practices. The work was conducted in the scope of KYKLOS 4.0 H2020 project aiming to create a cyber-physical ecosystem with pilot projects in healthcare, transport (e.g., aerospace, maritime, automotive), and different manufacturing sectors. In these complex scenarios requiring energy efficiency and waste management, interoperability must adopt relevant standards. Our contribution distinguishes the dimensions for selecting circular manufacturing standards and presents a list of examples. Moreover, a recent bibliometric analysis is presented in two leading databases, WoS and SCOPUS. The findings were essential to support our standardization choices.

Some limitations must be stated. First, standardization of circular manufacturing is a nascent topic. Therefore, the research team integrated the literature on interoperability standards, manufacturing, and circular economy, which later contrasted with insights collected from the industry and academic partners of KYKLOS 4.0. The list presented in the appendix can be improved in the future with specific standards for this field and exploring other areas not restricted to manufacturing. Second, our purpose is not to prescribe standards for circular manufacturing but to explain the dimensions that must be considered and provide examples for each one. Although including relevant economic sectors, the context of KYKLOS 4.0 pilot projects does not represent the entire manufacturing industry.

The future work in this field is promising for theory and practice. On the one hand, it will be interesting to create a systematic process of interoperability standards lifecycle management for circular manufacturing: the steps to identify, select, assess requirements, test compliance, and continuously improve. Foundational studies aiming at interoperability standards selection are a good starting point [21]. Interoperability standardization is central to cyber-physical ecosystems, but the sources of standards are vast, some are redundant, and its success will depend on industry adherence. On the other hand, the research team aims to identify a final list of interoperability requirements for circular manufacturing compliant with the standards presented in the appendix. The list will be validated in the project components deployed in each use case. Future work may study the impact of standardization in circular manufacturing innovation and both the benefits (e.g., auditability, coherence in the measurement of circular practices, scalability of cyber-physical devices in the configurable manufacturing network) and potential problems (e.g., few open standards, different opinions about data sharing formats in the ecosystem, or possible process inflexibility).

Appendix A. Interoperability standards for circular manufacturing in cyber-physical ecosystems

[Dimension] Description	**Standard Example**
[Architecture] Architecture development guidance for interoperability aligned with ArchiMate language	The Open Group Architecture Framework (TOGAF)
[Architecture] Business Process Model and Notation (BPMN) is a graphical representation for specifying business processes	Business Process Model and Notation (BPMN)
[Architecture] Language for ontology developments	W3C Ontology Web Language (OWL) 2
[Architecture] Modelling interoperability and selected standards	Open Group ArchiMate 3.1
[Architecture] Ontology definition	Semantic Sensor Network Ontology - W3C Recommendation
[Architecture] Reference architecture as a guide for interoperability between layers	IEC PAS 63088:2017 -Smart manufacturing - Reference architecture model industry 4.0 (RAMI 4.0)
[Architecture] Reference for the interoperability of sensing platforms	AIOTI WG3 High Level Architecture (HLA)
[Architecture] Reference model for IoT interoperability	Internet of Things Architecture (IoT-A)
[Compliance] A comprehensive list of standards (published and/or under development) in the scope of smart manufacturing	ISO/IEC TR 63306-2:2021 Smart manufacturing standards map (SM2) — Part 2: Catalogue

[Dimension] Description	Standard Example
[Compliance] Alignment with existing popular certification schemas in manufacturing: Quality management systems – requirements	ISO 9001:2015 Quality management systems — Requirements
[Compliance] Guidance for quality measurement data	ISO 23952:2020 Quality Information Framework (QIF)
[Compliance] Guidance for technical product documentation	ISO 8887-1:2017 Technical product documentation — Design for manufacturing, assembling, disassembling, and end-of-life processing — Part 1: General concepts and requirements
[Compliance] Guidelines for quality management systems auditing and environmental management systems auditing	ISO 19011:2018 Guidelines for auditing management systems
[Compliance] Protection of personal data	Directive 95/46/EC The Data Protection Directive
[Compliance] Vision for factory interoperability at the organizational and regulatory level	EFFRA vision for a manufacturing partnership in Horizon Europe 2021-2027
[Data Exchange] Adopt Linked Data paradigms - interfaces for semantic interoperability over ontologies for internet-connected objects within the physical world middleware while an open reference Support interoperability across different IoT ecosystems	The SPARQL Protocol and RDF Query Language
[Data Exchange] AMQP is an open message queuing protocol with a layered architecture.	ISO/IEC 19464:2014 Information technology — Advanced Message Queuing Protocol (AMQP) v1.0 specification
[Data Exchange] Contains specifications for agent management, including agent management services, agent management ontology, and agent platform message transport	FIPA Agent Management Specification
[Data Exchange] Data exchange format	ISO/IEC 21778:2017 Information technology — The JSON data interchange syntax
[Data Exchange] Data storage indications: AutomationML (Automation Markup Language), based on XML to manage engineering information	IEC 62714 Automation Markup Language - AutomationML
[Data Exchange] Guiding reference for manufacturing operations and control domain	ISO/IEC 62264 - Enterprise-Control System Integration – ISA 95
[Data Exchange] Interoperability of sensing platforms	Specifications for Machine-to-Machine (M2M) communications systems and the IoT - oneM2M
[Data Exchange] Interoperable communication	OPC Foundation Open Platform Communication Unified Architecture / IEC 62541 OPC Unified Architecture
[Data Exchange] Modbus provides serial communications protocol to connect industrial devices	Modbus protocol messaging structure
[Data Exchange] Open digital twin for product lifecycle interoperability	ISO 10303 series: Industrial automation systems and integration — Product data representation and exchange
[Data Exchange] Provides a lightweight messaging protocol: publish/subscribe messaging transport for connecting remote devices	OASIS standard messaging protocol for the Internet of Things (MQTT)
[Data Exchange] Recommendations for file formats, including comma-separated values	RFC 4180 Common Format and MIME Type for Comma-Separated Values (CSV) Files
[Data Exchange] Standard file format for data exchange -a set of file formats, libraries, and tools for storing and managing large scientific datasets	Hierarchical Data Format (HDF) version 5
[Data Exchange] XML documents for production floor planning and scheduling in manufacturing industries, and transactional exchange patterns for operations management contexts	OASIS Production Planning and Scheduling (PPS)
[Intelligence] Principles for digital twin developments in manufacturing	ISO 23247-1:2021 Automation systems and integration — Digital twin framework for manufacturing — Part 1: Overview and general principles

[Dimension] Description	Standard Example
[Security] Information security in the system	ISO/IEC 27000:2018 Information technology — Security techniques — Information security management systems — Overview and vocabulary
[Sustainability] Circular manufacturing guidance: Environmental management systems.	ISO 14001:2015 Environmental management systems — Requirements with guidance for use
[Sustainability] Circular manufacturing principles	BS 8001:2017 Framework for implementing the principles of the circular economy in organizations – guide
[Sustainability] Circular manufacturing principles: Eco-design	Directive 2009/125/CE (RD 187/2011) Eco-design
[Sustainability] Circular manufacturing principles: Environmental conscious design (ECD) suggests principles of life cycle thinking and integration of ECD into management practice	IEC/DIS 62959: Environmental conscious design (ECD) — Principles, requirements, and guidance
[Sustainability] Circular manufacturing principles: Guidance for product design and use considering different levels of certification to comply with cradle-to-cradle principles	Cradle to Cradle Certified™ Product Standard - C2CCertified
[Sustainability] Circular manufacturing: guidance for cost flow	ISO 14051:2011 Environmental management — Material flow cost accounting — General framework
[Sustainability] Circular manufacturing: Waste Framework Directive	Directive 2008/98/EC Waste Framework Directive
[Sustainability] Requirements and guidelines for life cycle assessment: goal and scope of the LCA, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), interpretation, reporting and review	ISO 14040: 2006: Environmental management – Life Cycle Assessment – Principles and framework (confirmed 2016)
[Sustainability] Product Interoperability, integration, and architectures for enterprise systems and automation applications	ISO 20140: Automation systems and integration — Evaluating energy efficiency and other factors of manufacturing systems that influence the environment
[Sustainability] Requirements and a structure for data documentation and exchange of Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI) data, thus permitting consistent documentation of data, reporting of data collection, data calculation, and data quality	ISO/TS 14048:2002 Environmental management — Life cycle assessment — Data documentation format

Note: Domain specific standards are omitted from this summary list (e.g., ISO 16739)

Acknowledgements

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