European Research project ALICIA: Recommendations for Standards on the Reuse of Production Resources

alicia – assembly lines in circulation

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Executive summary

The white paper provides an overview of the standardization potential identified as part of the European research project ALICIA. ALICIA aims to promote the reuse of assembly lines and contribute to a circular economy to improve the resilience of European supply chains. In this context, the importance of standards that can extend the life cycle of industrial equipment and promote efficient use of resources is emphasized. The main challenges here are the lack of standardization in the documentation of end-of-life equipment, the assessment of the sustainability of reused systems and the safe integration of reused machines into modern infrastructures. This white paper provides recommendations for standards for the reuse of production resources that are based on the principles of the circular economy and are intended to promote innovation, market equity and sustainability in the industrial sector.

General overview of the ALICIA project

The European research project ALICIA (Assembly Lines in Circulation) promotes the reuse of assembly lines, thereby contributing to the circular economy and the resilience of European supply chains. At its core is a digital platform that assists companies with internal management and external trade of (used) production resources. This is realized by the ALCIA marketplace, which is complemented by a range of digital tools, from AI-powered decision-making tools to digital twins for operating lines. These tools are designed to minimize uncertainties in the procurement and integration of second-hand equipment. In the long term, this should enhance the sustainability of commissioning new assembly lines and increase the availability of assembly systems by including second-hand resources in the market.

Therefore, ALICIA addresses the following challenges:

- the lack of standardization in the documentation of legacy equipment;
- the sustainability assessment of reusing assembly systems and the data required for this;
- the technical integration of older machines into modern Industrial Internet of Things infrastructures;

- the integration of IT security into the entire reuse cycle;
- acceptance problems relating to circular business models;
- ethical issues in the integration of human-related data.

ALICIA uses a four-stage development model: comprising requirements analysis, tool development, laboratory testing, and validation in real industrial applications.

1) In the **Specification** phase, the industry's requirements are collected through user surveys and transferred into a systematic functional concept. The aim is to identify the potential for reuse and define the needs of user groups.
2) The **Development** phase transfers this into the digital tools' specifications, such as AI-based decision support systems, interfaces for marketplaces, and digital twins. These tools are intended to facilitate the evaluation, selection, and integration of used equipment. Afterwards, the tools are implemented.
3) Within the **Integration and Validation** phase the tools are integrated and tested in a laboratory environment. This protected environment allows functionality, interoperability and user-friendliness to be tested and optimized iteratively.
4) Lastly, the **Demonstration** phase involves validating the tools in two industrial use cases from the automotive and electrical industries. After testing the effectiveness of the digital solutions in real operations, the requirements necessary for scaling the ALICIA marketplace and its digital tools are determined.

ALICIA and standardization

Standardization plays a key role in the ALICIA project under the leadership of the German Institute for Standardization (DIN). The project's standardization task aims to raise awareness of existing standards in the project and to integrate the results of ALICIA into ongoing standardization initiatives. An overview of relevant existing standards ensures that the project's developments are compatible with current solutions and products on the market, avoiding redundant efforts by recognizing existing technologies. By applying established standards, ALICIA incorporates the current state of the art into its processes, promoting seamless integration into the broader industry framework.

In order to integrate the results of ALICIA into standardization, the project established a liaison to ISO/TC 184 *Automation systems and integration*. Further, ALICIA identified potential for new standards, but for various reasons these were not translated into new standardization documents within the project duration.

The aim of this white paper

This white paper sets out the potential for new standards identified as part of the ALICIA project. It aims to raise awareness of the need for these standards and provides concrete examples where their existence could have simplified project activities. For each proposed standardization idea, the relevant knowledge gained during the ALICIA project is presented in detail to provide a basis for the development of these new standards. The white paper is intended to encourage the relevant standardization bodies to include these proposals in their work program. By providing initial guidance and highlighting applicable findings from the ALICIA project, the white paper aims to facilitate meaningful progress in standardization.

Standardization potentials and needs identified within ALICIA

The ALICIA project conducted a collaborative workshop with the European research project CIRC-UITS (GA No. 101091490) to explore the need for new standards, leveraging shared insights for mutual benefit. Five key areas for new standards related to the ALICIA project emerged, in the following called standardization potentials:

1) Common processes for assessing environmental impacts of second-hand equipment;
2) Common data format for machine data;
3) Requirements for the reuse of production equipment;
4) New standards for estimating the Remaining Useful Life (RUL) of machinery components;
5) Common standards for equipment spare parts and refurbishing manuals to ensure high-quality refurbishment.

For the first three potentials in the following an overview will be given of the detailed needs which arouse during the ALICIA project and the results from the project which could possibly serve as a basis for a future new standard in the form of some kind of factsheets. During the detailed discussions on those potentials, it became clear that the potential 1 on “Common processes to assess environmental impacts of second-hand equipment” and potential 3 on “Requirements for the reuse of production equipment” are at least partly heading in the same direction, which is why both are tackled in one factsheet. With regard to potential 4 and 5 it became clear that there is a need for standards with regard to RUL and equipment spare parts / refurbishing manuals but that a useful factsheet on both topics cannot be developed due to a lack of results within ALICIA project in that regard. Nevertheless, in the following the identified needs in this regard are described.

Factsheet on optimizing equipment reuse: creating standards for environmental impact assessment and operational requirements

Description of the standardization need

In the context of reusing production equipment, evaluating environmental impacts is crucial. Because the saved environmental impact from decreasing the production of new equipment may be outweighed by the higher environmental burden from operating old technology. Currently, there are no established standards for assessing the environmental implications of reused equipment. Developing a standard should focus on adapting traditional Life Cycle Assessment (LCA) methods to measure the environmental effects of second-hand equipment. Current methods do not consider the remaining lifetime of reused machines and equipment. Furthermore, there is a lack of clarity regarding the necessary data for making informed decisions about equipment reuse. Challenges also include selecting appropriate assessment units and defining the boundaries for LCA of second-hand equipment. Addressing these issues is essential for a comprehensive understanding of the environmental impact of equipment reuse. Due to that the development of a standard on “Common processes to assess environmental impacts of second-hand equipment” is recommended. Such a document could be widely utilized by LCA practitioners, including consulting companies, manufacturers, and organizations conducting LCAs. It would also be valuable for manufacturing companies considering the purchase of new or used machines, research projects focusing on the circular economy, and future policymakers and authorities. In a circular economy, it is crucial to consider not only recycling but also other strategies such as refurbishment and reuse. This broader perspective makes the concept relevant to various stakeholders, not just those in assembly line manufacturing, but across other manufacturing sectors as well.

In addition to assessing environmental impacts, specific requirements must be established to facilitate the practical reuse of production equipment. Reusing production equipment offers a significant opportunity to cut costs and enhance sustainability. However, integrating reused equipment into assembly lines is challenging due to the lack of standardized terms, definitions, and calculations for key performance metrics like reliability, maintainability, efficiency, and cycle time. Although existing standards provide general definitions, they fall short of addressing the unique demands of reused equipment in assembly lines, leading to inconsistent practices and varying customer expectations. This inconsistency complicates decision-making and disrupts operational continuity. Furthermore, companies employ diverse terminologies and guidelines for advising customers on procuring reused equipment, resulting in a fragmented communication landscape and a lack of uniform standards. Such fragmentation hampers the ability of buyers to evaluate the quality and suitability of reused equipment effectively. Therefore, a comprehensive standardization framework for the requirements for the reuse of production equipment is essential to optimize performance, ensure clear communication, and support informed decision-making across industries.

Existing standards with regard to the assessment of the environmental impacts of second-hand equipment

ISO/TC 323 Circular economy

- ISO 59020:2024 Circular economy - Measuring and assessing circularity performance

ISO/TC 207 Environmental management

- ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework
- ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines

ISO/TC 184 Automation systems and integration

- ISO 18828-4 Industrial automation systems and integration - Standardized procedures for production systems engineering - Part 4: Key performance indicators (KPIs) in production planning processes
- ISO 22400 series Automation systems and integration - Key performance indicators (KPIs) for manufacturing operations management

IEC/TC 65 Industrial-process measurement and control

- IEC 62890 Industrial-process measurement, control and automation - Life-cycle-management for systems and components

ITU

ITU-T L.1023:2023 Assessment method for circularity performance scoring

Existing standards with regard to the reuse of production equipment

ISO/TC 207 Environmental management

- **ISO 14051:2011** Environmental management - Material flow cost accounting - General framework
- **ISO 14052:2017** Environmental management - Material flow cost accounting - Guidance for practical implementation in a supply chain
- **ISO/TS 14074:2022** Environmental management - Life cycle assessment - Principles, requirements and guidelines for normalization, weighting and interpretation

IEC/TC 56 Reliability and maintainability

IEC 60300-3-3:2017 Dependability management - Part 3-3: Application guide - Life cycle costing

IEC 61124:2023 Reliability testing - Compliance tests for constant failure rate and constant failure intensity

IEC 62309:2024 Dependability of new products containing reused parts and life-extended products

IEC/TC 111 Environmental standardization for electrical and electronic

IEC/TS 63428 Guidance on material circulation considerations in environmentally conscious design

CWA

CWA 18038:2023 Methodology for managing maintenance strategy and remanufacturing projects of large industrial equipment

Requirements for a new standard on the assessment of environmental impacts of second-hand equipment

The establishment of a comprehensive standard is needed for assessing the environmental impacts of second-hand equipment, particularly focusing on the reuse processes involving assembly line equipment. This standard should encompass several critical components:

1. **Similar Steps as Traditional LCA (e.g., ISO 14040):**

A new standard should be consistent with established LCA procedures, following the four steps outlined in ISO 14040 (goal definition, inventory analysis, impact assessment, and interpretation). However, additional sections specific to second-hand equipment assessments shall be incorporated.

2. **Methodology for LCA of Second-Hand Equipment:**

A specific methodological framework for conducting Life Cycle Assessments on second-hand equipment has to be outlined, considering the unique characteristics and impacts related to these types of assets. This should involve detailed guidelines on goal definition and defining the unit of assessment, tailored specifically to second-hand equipment. Particular attention should be paid to the boundary conditions, such as the estimation of the remaining lifetime and the question under which circumstances the environmental impact during production of the equipment should be transferred to the second lifetime.

In addition, guidelines are needed for the comparison to the first life cycle assessment, particularly when the first-life LCA covers a shorter timespan than the current age of the equipment being reused rather than scrapped.

3. **Circularity Key Performance Indicators (KPIs):**

Circularity KPIs shall be defined for the reuse cycles and remanufacturing processes for different types of used appliances. It is important to detail how to set the scope, define the assessment unit, and evaluate the KPIs for reuse and remanufacturing processes, such as reliability, maintainability, efficiency, and cycle time. Further, the indicators should measure aspects such as material flow, second-life time, and other measures of circularity to ensure a comprehensive assessment. Unified methods for measuring and calculating these KPIs should be established to ensure consistency and reliability across different applications and industries. It shall be considered specifying the time dimension explicitly, including estimating the remaining lifetime and determining under what circumstances the environmental burden from production should be carried forward to the second lifetime.

4. **Hotspots in Reuse Processes:**

Specific guidelines for identifying and analyzing environmental hotspots, in the reuse process, have to be included. This will help practitioners to focus on areas with significant environmental impacts during the reuse and remanufacturing stages.

5. **Calculating the energy consumption and CO_2 emissions**

A guideline should be given on how to calculate the energy consumption of individual machines and the entire production line for different states over a simulated period using MTBF and MTTR parameters.

Insights and Results from ALICIA

General

Within ALICIA, the existence of a standard on the assessment of environmental impacts of second-hand equipment would have significantly streamlined the environmental assessment process, particularly within the evaluation of ethical (including AI), societal (including human-centricity), and environmental (LCA) implications of the technologies. It would have eliminated the time-consuming efforts spent on defining frameworks, scope, units, assumptions, and data requirements especially during the project's early stages. This would have been particularly helpful for analyzing the complex interactions between second life stages and refurbishment in relation to "normal" life cycle assessment. Current standards for LCA, particularly when applied to used equipment, are inadequate; hence, a new standard would be invaluable. It would facilitate the establishment of baselines and enable validation of LCA results, promoting comparability across studies. In addition, such a standard would have assisted within ALICIA embedding environmental impact minimization into the evaluation and ranking of manufacturing equipment. Moreover, it would have provided clarity regarding data requirements for LCA evaluations.

The LCA framework from ALICIA

Within the ALICIA project, we developed an LCA framework specifically tailored to used manufacturing equipment. A core assumption of this framework is that it captures only the additional environmental burden associated with reuse. As such, the impacts incurred during the equipment's initial life -up to the point of resale- and those related to its eventual disposal are excluded. Instead, the framework focuses on the refurbishment phase (if required), transportation to the new site, and the second-use phase. Developed during the early stages of the ALICIA project, the framework was designed to address the methodological challenges of applying conventional LCA principles to second-life equipment, where lifecycle stages may overlap or repeat in non-linear ways. ISO 14040:2006 was used as the basis for the new framework to ensure methodological consistency while accommodating limited data availability and the need for efficiency. The system boundaries and functional unit -defined as one unit of output produced during the second-use phase- enable meaningful comparison across equipment with varying remaining lifetimes, productivity, and performance levels. This structured approach provides a robust foundation for integrating reuse scenarios into lifecycle thinking. The framework is illustrated in Figure 1.

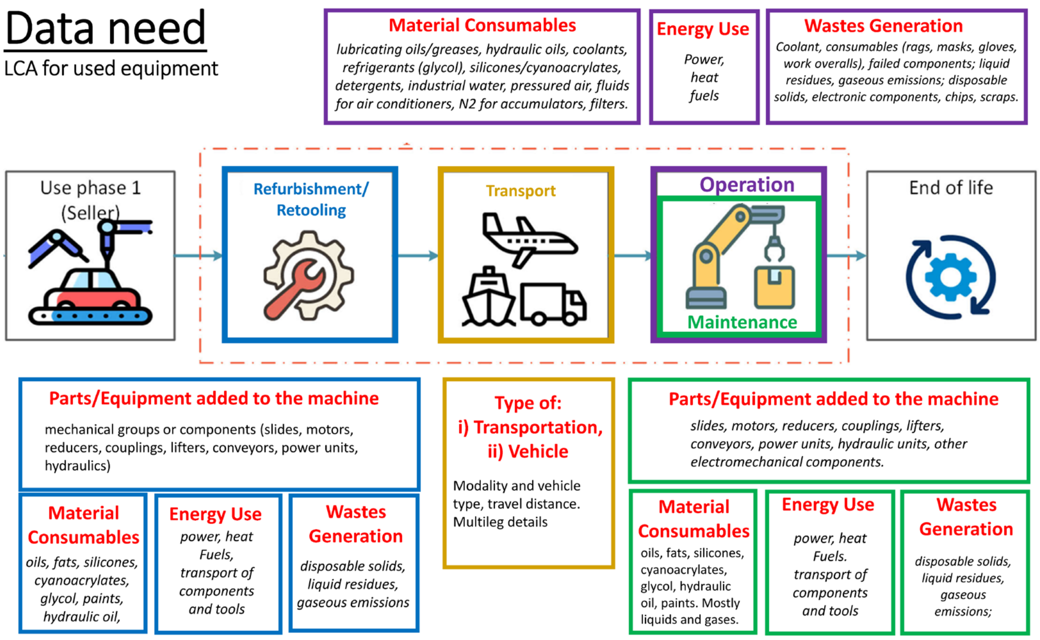

Figure 1: Use phases and data needed in the LCA framework from the ALICIA project

As shown in Figure 1, implementing this framework requires a comprehensive dataset for each of the key phases in the equipment's second life. Critical data inputs include energy use (power, heat, and fuel consumption), material consumables (e.g., lubricants, hydraulic fluids, water, and pressurized air), and waste generation (including disposable solids, liquid residues, and gaseous emissions). During refurbishment and maintenance, additional energy demands -such as those related to tool use and transport of replacement components- must be captured. These phases also generate additional waste, including failed components, used consumables (e.g., rags and gloves), and auxiliary substances like detergents. Furthermore, components added to the equipment -such as motors, reducers, lifters, hydraulic units, or other electromechanical parts- carry their own embedded environmental burden from manufacturing and logistics and should be included in the analysis. For the transport phase, relevant data includes transport modality, vehicle type, travel distance, and multi-leg routing, including warehouse storage and transfer points. This detailed input structure ensures that the environmental impacts, attributable solely to the reuse scenario, are properly quantified while remaining consistent with established LCA practices.

The LCA framework developed in the ALICIA project could enhance a new standard by providing a tailored approach that isolates additional environmental burdens specific to reuse and second-life stages. Key elements include methodological consistency based on ISO 14040:2006, clear system boundaries, and functional units that facilitate meaningful comparisons across diverse equipment lifetimes and performance levels.

Sustainability KPI definitions from ALICIA

In the ALICIA project, sustainability KPIs were researched and chosen by project experts to measure and compare the environmental sustainability of different second-hand machines. This is crucial, as milling and turning machines, for example, have their highest environmental impact during the use phase due to their high energy consumption (CECIMO 2019); The sustainability key performance indicators were determined using literature research. Afterwards, they were categorized and ranked by experts using the criteria specified in ISO 22400. All KPIs above a certain threshold were then chosen for the project and integrated in the ALICIA ontology. Table 1 shows the chosen KPIs. In total, eleven KPIs were chosen across the categories material, energy, emissions, and waste.

Table 1: Definition of the ALICIA sustainability KPIs (H: higher is better, L: lower is better, PE: production equipment)

KPI	Category	Description	Unit	Trend	Range
Total amount of material	Material	Total amount of material needed to produce/repair/remanufacture the PE	kg	L	0 – ∞
Raw material	Material	Amount of raw material that has been used to produce/ repair/ remanufacture the PE	kg	L	0 – ∞
Recycled material	Material	Amount of recycled material (replacing primary material) that has been used to produce/ repair/ remanufacture the PE	kg	H	0 – 100
Critical material	Material	Amount and type of critical material that has been used to produce/ repair/ remanufacture the PE	kg	L	0 – ∞
Transportation of piece of equipment	Energy	The environmental burden of the transportation of the piece of production equipment from the seller to the buyer depending on the mode of transportation	CO_2 equi-valent	L	0 – ∞

Energy consumption	Energy	Total energy consumption (including all types of energy)	kWh	L	0 – ∞
Gas emissions	Emissions	Total gas emissions of the PE during the use phase	kg	L	0 – ∞
CO_2 emissions	Emissions	CO_2 emissions during the use phase	kg	L	0 – ∞
Total amount of waste	Waste	Total amount of all the waste that does not concern the product but has been used for operation (e.g., lubricants, spare parts…)	kg	L	0 – ∞
Hazardous waste	Waste	Amount of hazardous waste (possible threat to the environment or human health) that does not concern the product but has been used in the use phase	%	L	0 – 100
Disposal and end-of-life of production equipment	Waste	Environmental burden on the environment due to the disposal of the piece of production equipment	CO_2 equi-valent	L	0 – ∞

The ALICIA project's collection of sustainability KPIs could contribute to a new standard by providing a structured method to assess and compare the environmental sustainability of second-hand machines. Essential content includes expert-evaluated indicators across material, energy, emissions, and waste categories, guided by ISO 22400 criteria, which focus on the significant environmental impact during the use phase.

Requirements for a new standard on the reuse of production equipment

Besides the assessment of the environmental impact, further points have to be considered for the reuse of production equipment. The following points were identified as critical aspects that should be considered in the development of such a standard:

1. **Cost effectiveness and viability of equipment reuse**

It should be ensured that reused equipment is economically viable for end-users by providing guidelines for Life Cycle Cost (LCC) calculations. This should involve assessing the total cost over the equipment's life, including acquisition, operation, maintenance, and disposal costs.

2. **General applications beyond integration into existing lines**

The standard should not be limited to integrating reused equipment into existing production lines. Guidelines applicable to various scenarios (including greenfield and brownfield scenarios) should be provided, offering a broader perspective on equipment reuse.

A standardized process should be developed to guide sellers and buyers through the reuse of equipment, ensuring transparency and consistency. This should include outlining critical factors for informed decision-making.

A practical checklist should be created to assist stakeholders in assessing reused equipment before purchase and implementation.

3. **Evaluating reliability, maintainability, availability, and efficiency**

Estimating the efficiency of a production line requires calculating the reliability and maintainability of machines with both used and new parts. Variable failure rates arise due to overlapping random and wear failures. A standard should address this, including the challenge of how to handle this without knowing the actual usage duration and maintenance history of unchanged components. Therefore, guidelines should be given to both end users and manufacturers to evaluate the suitability of each machine to ensure the overall production line efficiency.

4. **Challenges and compliance in repurposing production equipment**

If extensive modifications radically repurpose original machines, they become new machines requiring CE marking and compliance with 2006/42/EC Annex II A when introduced to the EU market. However, standardized guidelines are needed to repurpose longstanding machinery into new machines.

Insights and results from ALICIA

General

Within ALICIA the existence of a standard on reuse of production equipment would have facilitated several aspects of the project like estimates of energy requirements and consumables. Additionally, it would have simplified the development of the marketplace/platform, ensuring that user needs and required data were apparent from the outset. Such a standard would have aided in defining user requirements, use cases, and the content of requests for quotations (RFQ) to generate more accurate proposals. Furthermore, it would have streamlined the estimation of remaining useful life and the identification of viable business cases. Lastly, the definition of key performance indicators (KPIs) for calculation by Digital Shadow/Digital Twin (DS/DT) systems would have been more straightforward, further enhancing the project's efficiency and impact.

Digital Twin / Digital Twin framework from ALICIA

The ALICIA project has developed a two-phase decision-support framework integrating AI-Matchmaking, Digital Shadow (DS), and Digital Twin (DT) technologies. This framework plays a critical role in supporting the reuse of second-hand production equipment, both during the procurement and production phases.

In the procurement phase, the process is initiated by the AI-Matchmaking component, which generates a set of optimal equipment or production line configurations based on user needs, technical requirements, and available assets. These configurations are pre-evaluated using utility scores and suggestions based on historical and contextual data, including estimated Remaining Useful Life (RUL) and CO_2 impact.

Following this, the Digital Shadow (DS) module narrows down the proposed solutions by ranking them using a detailed KPI-based comparison, which includes:

- Cycle time efficiently
- Overall Equipment Effectiveness (OEE)
- Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR)
- Energy consumption
- Scrap rate
- Downtime cost and throughput rate
- Available industrial space
- Production line budget

If historical parameters are incomplete or unavailable (e.g., due to confidentiality), the DS Simulation Framework performs estimations to simulate missing input values, ensuring complete and consistent KPI evaluations.

In the production phase, the Digital Twin (DT) is deployed to support factory owners in ramp-up, operational optimization, and predictive maintenance. The DT continuously monitors the reused equipment in real-time, calculates updated KPIs, and optimizes production based on performance feedback. It also enables transformation of Asset Administration Shell (AAS) models to formats usable by the AI-System Analyzer, including best settings for process and design parameters.

Moreover, the DT functionality helps recirculate production resources—by feeding back equipment lifecycle data into the ALICIA platform—thus enriching future DS evaluations for subsequent reuse cycles (third-life and beyond).

The DS/DT framework from ALICIA contributes to reuse-related standardization efforts by:

- Structuring data pipelines and simulation logic for reliable second-life equipment assessment
- Providing a foundation for standardized KPI definitions and calculations
- Supporting interoperable API interfaces for marketplace integration (DS/DT and DS Simulation APIs)
- Enabling traceability of refurbishment actions and lifecycle history to meet regulatory and operational needs (e.g., CE compliance)

By formalizing how reused assets are selected, validated, and monitored, this framework promotes transparency, consistency, and circular economy principles—key factors in the development of future industry standards.

The ALICIA project's decision-support framework could serve in a new standard for the reuse of production equipment by integrating AI-Matchmaking, Digital Shadow, and Digital Twin technologies to enhance transparency and lifecycle management. Key content involves structured data pipelines for assessing second-life equipment, standard KPI calculations, interoperable APIs for marketplace integration, and traceability of refurbishment actions, which collectively advance circular economy principles and compliance with regulatory standards.

Factsheet on advancing a standard data format for manufacturing machinery

Description of the standardization need

The rapid advancement of automation within the manufacturing industry underscores the critical need for efficient data collection and utilization from various machines. Currently, multiple data formats coexist, dependent on different providers, and while some technologies have emerged as de-facto standards, there is no universally accepted framework that transcends the diverse ecosystem of Original Equipment Manufacturers (OEMs), vendors and integrators.

A standardized framework for a common data format is essential for ensuring seamless communication between industry machines and optimizing the availability of production data. The creation and adoption of a standardized common data framework could facilitate collaboration and ensure that stakeholders across the industry can benefit from interoperability, especially regarding the reuse of equipment.

Such a standard should cater to machine OEMs, end-users, and machine integrators, by providing a holistic approach applicable to all data-producing machinery. This framework could offer significant advantages to the maintenance industry and industrial software producers, promising enhanced efficiency and interoperability.

Existing standards in this area

ISO/TC 184 Automation systems and integration

- **ISO 3592**:2000 - *Industrial automation systems - Numerical control of machines - NC processor output; File structure and language format*
- **ISO 6983-1**:2009 - *Automation systems and integration - Numerical control of machines - Program format and definitions of address words - Part 1: Data format for positioning, line motion and contouring control systems*
- **ISO 10303 series** - *Industrial automation systems and integration — Product data representation and exchange*
- **ISO 13584 series** - *Industrial automation systems and integration*
- **ISO 15531 series** - *Industrial automation systems and integration*
- **ISO/CD 23726-3** - *Automation systems and integration — Ontology based interoperability - Part 3: Industrial data ontology*
- **ISO/AWI 23726-2** - *Automation systems and integration — Ontology based interoperability - Part 2: Vocabulary*
- **ISO/AWI 23726-100** - *Automation systems and integration — Ontology based interoperability - Part 100: Schedule data ontology*

ISO/TC 108 Mechanical vibration and shock

- **ISO 13374-1**:2003 - *Condition monitoring and diagnostics of machines - Data processing, communication and presentation - Part 1: General guidelines*

ISO/TC 159 Ergonomics

- **ISO/TR 25060**:2023 - *Systems and software engineering - Systems and software Quality Requirements and Evaluation (SQuaRE) - General framework for Common Industry Format (CIF) for usability-related information*

NISO (National Information Standards Organization)

- **NISO Z39.2-**1994 *(R2026):2016* *Information Interchange Format*

SAC/TC 62 Terminology (China national institute of standardization)

- **GB/T 18155**:2000 - *Terminology work-Computer applications-Machine-readable terminology interchange format(MARTIF)-Negotiated interchange*

IEC/SC 3D Data sets for libraries

- **IEC 61360 series** - standard data element types with associated classification scheme

DIN

- **DIN SPEC 16592**:2016 - *Combining OPC Unified Architecture and Automation Markup Language*

Requirements for new standards

A comprehensive framework for a common data format to effectively capture and represent machine data, including production data and machine condition should be established. Such a framework should describe the general properties of machines and create structure in a generic format. Additionally, it should outline a minimum set of requirements necessary to describe a machine's attributes and performance. Below are the specific requirements for such a standard:

- Asset Metadata:
  - Asset type and unique identifier
  - Manufacturer and Model Information
  - Installation Data
  - Usage Hours / Runtime

- Operational Data:
  - Status Indications (e.g. Off, On, Idle)
  - Cycle Times and Production Counts
  - Process variables (e.g. Temperature, RPM, Speed, Torque, depending on process and asset)
  - Operating Mode (e.g. Manual, Automatic, Maintenance)

- Maintenance Data:
  - Condition Monitoring / Sensor Data (e.g. Vibration, Noise, Lubricant Levels, Environmental Conditions)
  - Maintenance Logs
  - Failure History
  - Parts Replacement / lifespan tracking

- Control and Configuration Data:
  - PLC Settings
  - Tuning parameters
  - Firmware and Software versions

- Safety and Compliance Data:
  - Emergency Stop activations
  - safety interlock status
  - Incident Reports
  - Compliance Logs
  - Environmental impact metrics

- Capability Modelling:
  - General description of machine capabilities: The machine functions and specifications such as range, payload, compatible material types, grip arm weight, etc. should be described.

- Data input and formulas: The essential data inputs and computational formulas needed for effective performance KPI modelling should be identified. The challenges in data modelling specific to capability representation should be addressed.

The framework should be applicable to both new industrial machines and second-hand equipment. This ensures wide applicability and supports the measurement of the machine's status across varying equipment conditions.

The establishment of these requirements would ensure a robust, standardized framework that enhances machine interoperability and efficient data utilization, benefiting the manufacturing industry's diverse stakeholders.

Insights and results from ALICIA

General

A standardized format for machine data aims to ensure that all involved parties - factory owners, equipment sellers, and system integrators- share a common understanding of the data being requested. By establishing this shared understanding, the standard provides a unified framework for collecting relevant information, promoting clarity, consistency, and completeness. This foundation enables several key benefits in the integration of digital technologies within ALICIA. For instance, the structured data format can be directly utilized by the AI Matchmaker and Digital Shadow components, supporting intelligent equipment selection and accurate digital system representation. It also helps optimize middleware requirements by creating a clear structure for data processing, thereby enhancing interoperability. When modeling the Asset Administration Shell (AAS), a common data format would have served as a basis to speed up the design process and simplify integration. A standardized format would also have facilitated easier the specification of Digital Twin APIs by ensuring seamless data communication and optimizing performance. In addition, it would have simplified the design and implementation of interfaces between middleware and digital twin systems and improved overall connectivity. Finally, importing historical data into digital systems would have been easier, enabling consistent and reliable data usage.

ALICIA equipment information input structure and description of general properties of machines

During the design and implementation of the ALICIA industrial equipment information input structure, multiple key aspects were discovered.
A hierarchically structured data model is necessary to accurately capture asset structures and component relationships.
To support diverse equipment classes, the schema must remain generic and extensible and ideally aligned with industry standards to ensure interoperability across systems.
Given that data entry is typically performed by operational personnel, the input process must present minimal friction to encourage consistent and accurate input.

The schema must be scalable to accommodate large asset volumes and support lifecycle data evolution.

Robust validation rules and controlled vocabularies are essential to maintain data integrity. Additionally, given the potential sensitivity of equipment data, such as proprietary configurations, operational parameters or historical production data, appropriate access controls and clear communication regarding data usage and protection are paramount for user trust.

ALICIA Asset Administration Shell models created as part of use case demonstrators

Over the course of developing Asset Administration Shell (AAS) models for the ALICIA use case demonstrators, the project have found that a greater focus on early integration of standardized semantic references, such as using ECLASS and IEC-compliant identifiers, would have reduced downstream work and provided a more solid basis for cross component integration, as such semantic references enrich interoperability, reusability, and machine-readability across systems and domains.

Capability modelling for use case equipment in ALICIA

To enable detailed characterization and comparison of industrial equipment in ALICIA, capability modelling was applied as a foundational layer within the semantic representation of machines. This modelling was grounded in the MaRCO ontology (Järvenpää et al., 2019), which provides a structured, machine-readable framework for describing manufacturing resources, and their functional capabilities. This approach offered the following advantages:

- It enabled uniform and comparable descriptions of equipment capabilities across diverse machine types.
- Improved decision support, by enabling automated capability matching between process requirements and machine functions.

ALICIA Middleware Asset Adaptors

The development, deployment and integration of middleware asset adaptors for the ALICIA use case demonstrators highlighted the importance of standardized data structures, especially given the heterogeneous nature of potential assets both in age (newbuilt and legacy assets) and vendors. It proved greatly beneficial to transform captured asset data in the edge layer directly after ingress, providing greater downstream usability and maintainability. This not only simplified integration with connected ALICIA components such as the digital twin, but additionally enabled better data readability, the possibility of consistent historical data analysis and comparability between asset data of diverse vendors and ages.

Standardization potential 4: New standards for RUL (Remaining Useful Life) of machinery components

In the industrial sector, accurately estimating the Remaining Useful Life (RUL) of machinery components is critical for sustainability and cost-efficiency. Current practices lack clarity and consistency, prompting the need for new standards to define universal RUL estimation frameworks. Key focuses such a standard should include are:

- Establishing a comprehensive methodology for RUL estimation applicable across various machinery types.
- Ensuring consistency in terminology and methods.
- Specifying calculation methods using historical and real-time data.
- Clarifying roles and responsibilities among stakeholders like end-users and manufacturers.
- Emphasizing data requirements, management, and storage for reliable calculations.

This would support machinery reuse, enabling stakeholders to make informed decisions on maintenance, replacement, and integration, thus improving operational efficiency and equipment lifespan. Despite challenges, creating a standardized approach is essential for achieving consistency in RUL estimation across industrial contexts.

Standardization potential 5: Common standards for equipment spare parts or refurbishing manuals in order to ensure high quality refurbishment

The current refurbishing and remanufacturing landscape for industrial equipment faces a key challenge: lack of detailed technical information from original equipment manufacturers (OEMs) needed for high-quality refurbishment. To address this, new standards are needed for equipment spare parts and refurbishing manuals. These standards would:

- Define standardized criteria for high-quality refurbishing practices, ensuring reliability and performance comparable to new equipment.
- Enhance accessibility to repair processes and spare parts for third-party remanufacturers, promoting fair competition and reducing monopolistic control by OEMs.
- Boost consumer confidence by guaranteeing that refurbished equipment meets rigorous quality assurance criteria.
- Contribute to sustainability by extending the lifecycle of industrial equipment and promoting efficient resource use.

By establishing these standards, the industry can empower non-OEM stakeholders, ensure market fairness, and improve the quality of remanufactured equipment. This supports greater efficiency, sustainability, and innovation. Additionally, regulations requiring OEMs to disclose necessary information could facilitate these efforts, aiding stakeholders in assessing whether refurbishment is economically and environmentally viable.

Recommendations

This document recommends the development of standards that extend the lifecycle of industrial equipment and promote efficient resource use, fostering sustainability, market fairness, and innovation. It suggests empowering non-OEM stakeholders by improving the quality of remanufactured equipment and calls for regulations to require OEMs to disclose necessary information to evaluate the viability of refurbishing both economically and environmentally.

Conclusion

In conclusion, this white paper underlines the central role of standardization in promoting sustainability and efficiency in the industrial sector. The ALICIA project has identified significant potential for standardization, such as assessing the environmental impact of used machinery, establishing common data formats, defining requirements for the reuse of production equipment and creating standards for the remaining useful life of machine components (RUL) or spare parts for equipment, as well as refurbishment manuals. These efforts are aimed at enabling and improving the quality of remanufactured equipment in the first place. Standardization not only facilitates seamless integration into existing industrial frameworks but also promotes innovation and circular business models. Looking to the future, the document foresees an increased focus within standardization bodies on the topic of reuse of production equipment and the continued development of robust standards that take into account technical challenges in this regard and sustainability goals. As the industry increasingly embraces circular economy principles, the proposed standards promise to promote resilience and resource efficiency on a broader scale.

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