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Manufacturing X – Solutions for the Manufacturing Industry

Industrial Data Standards to Support Industrial Data Ecosystems

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Abstract. The digitalization of industrial production (Industrie 4.0 - the comprehensive digitalization of industrial production), science, and the public sector (Government 4.0 - the digitalization of public administration and the automation of work processes in the public sector) is converging to form a Global Integrated Data Space (GIDS). The concepts of Industrie 4.0 and the Industrial Internet of Things require standardized technologies, trustworthy and sovereign data ecosystems with interoperable protocols for data connection, exchange, transfer, and an integrated legal framework enabling automated smart data. These requirements apply equally to science and the public sector, even if the specifications and objectives differ, e. g., concerning the FAIRification of research outputs. The concept of FAIR Digital Objects (FDOs) as specified by the FDO Forum and its flavors of practical application (e. g. RO-Crates), according to the Digital Object Architecture (DOA), can serve not only within a domain or data space but also as cross-sector, cross-discipline and cross-data-space containers using the Digital Object Interface Protocol (DOIP) as a standard exchange protocol. Drawing on the practical experience of Manufacturing-X, the article demonstrates how industry, academia, and the public sector can learn from each other about FDOs, exchange protocols, and rights, leading to joint standardization efforts.

Keywords: Manufacturing-X, Factory-X, International Manufacturing-X Council, FAIR Digital Objects, DOIP, Government 4.0, Global Integrated Data Space GIDS

1. Introduction

Data ecosystems, digital twins, and the asset administration shell technology among others are crucial for the actual improvement of industrial competitiveness and design processes. Our article outlines the challenges and experiences of the last decade in the context of Industrie 4.0, i.e., the comprehensive digitalization of industrial production, in order to successfully master these requirements and harness them for the convergence of industry, academia, the public sector, and beyond [1] towards a Global Integrated Data Space (GIDS).

1.1 Roots of Industrie 4.0

Manufacturing-X is a success story. But how did it come about? It all started when the individual players feared for their data, had little trust, and were unaware of the benefits of digital collaboration based on digital services. The manufacturing industry works with global supply chains. Trust among the stakeholders, i.e., Original Equipment Manufacturer (OEMs) the supply chain SMEs are the binding glue. There is also a lack of vertical and horizontal data interoperability and high transaction costs. In addition, the small medium enterprises (SME) tend to be left out, even though they stand for about 90% of global manufacturing value adding. The Manufacturing-X data ecosystem seeks to overcome these challenges by creating an interoperable and federated ecosystem that promotes and develops industrial use cases with end-to-end solutions that also benefit SMEs. Over the last decade, key industrial players have worked together to create the necessary standards and ecosystem prerequisites. The challenge of integrating SMEs is one that Labs Network Industrie 4.0 (LNI 4.0) testbeds [2] is tackling in an example way. This takes place in a constantly changing, socially and ecologically committed corporate culture.

2. Industrial data economy requirements and challenges

After more than a decade of Industrie 4.0 development, manufacturers are transforming their industrial digital businesses into global, federated, interoperable, scalable and secure data spaces. Manufacturing companies are pursuing specific targets to make their businesses efficient, robust and transparent to achieve the goals of resilience, sustainability, and competitiveness. A key challenge continues to be the convergence of IT and OT (Operational Technology). A crucial aspect of convergence is the area of standardization. OT standards and norms are established and maintained over very long lifecycles i.e., several decades, while IT standards have shorter innovation cycles. OT also comprises long-term invested brownfield installations. Integrating IT systems using standards in brownfield environments (i.e., the immediate presence of existing environments) requires easy-to-use end-to-end solutions that work in very heterogeneous OT environments. For SMEs, these circumstances are critical factors for the success of the participation in digital ecosystems such as Manufacturing-X.

2.1 Manufacturing-X initiative

Manufacturing-X [3] is a program of the German Federal Ministry for Economic Affairs and Climate Protection (BMWK) launched in 2023. The aim is to strengthen the sustainability, resilience, and competitiveness of the industrial manufacturing sector by supporting effective, sovereign, and trustworthy data economy solutions and simplifying the use of data across company boundaries. Manufacturing-X aims to make the concept of Industrie 4.0 a reality across the entire industrial sector and beyond [4]. To overcome isolated solutions, Manufacturing-X pursues an inclusive approach. All relevant stakeholders are involved regardless of their needs and size, i.e., the SMEs' requirements and specific needs for the data ecosystem are explicitly considered.

In the context of Manufacturing-X, the building blocks to be combined are hardware, software, and business models in various dimensions and components that are assigned to the different domains:

- Policy and ethical components, such as the core principles of openness, inclusiveness, and fairness.
- Organizational components, such as the stakeholder engagement and an appropriate formal organizational form.
- Operational and implementation components based on common international standards.
- Conceptual and technical components like data ecosystem architectures, industrial digital twins, and semantic interoperability technologies such as Asset Administration Shell (AAS) [5], OPC UA [6], umati [7], etc, as well as data connector technologies such as the Eclipse Dataspace Components (EDC).

This open and inclusive approach has far-reaching consequences that differ from the previous silo mentality:

- Heterogeneous players concerning size, sector and objectives get involved.
- Under the umbrella of Manufacturing-X, competing solutions that use the same international standards for data exchange are promoted. Hence, the market will decide which approach proves successful.
- There are common data standards that all players develop and accept, which are binding and not subject to competition.

The projects within the Manufacturing-X program will contribute to a cross-industry data ecosystem. Catena-X has laid many of the foundational elements for all Manufacturing-X projects.

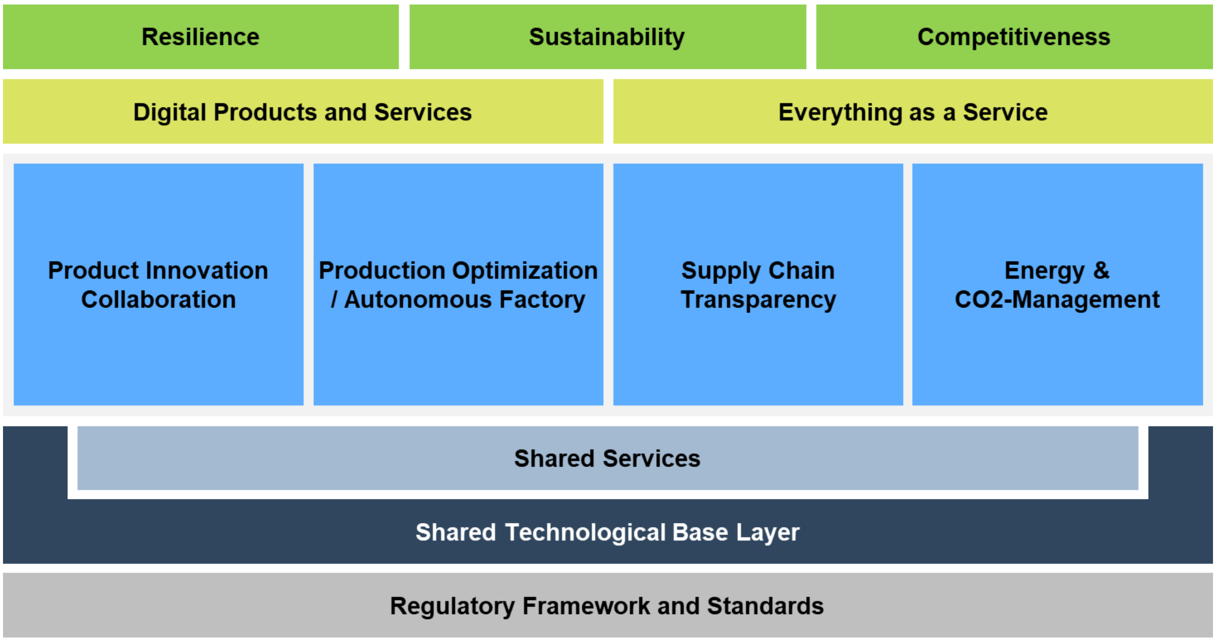

Figure 1. *Overall Architecture Digital Ecosystem Manufacturing-X [8]*

Fig. 1 is not a snapshot of Manufacturing-X but rather a core of elements and principles that will continue to evolve in the long term and serve as a compass for the coming decades. In the following, we present the topic of internalization and the Factory-X project derived from the Manufacturing-X architecture.

2.2 Manufacturing-X internationalization and lighthouse projects

Internationalization has been one of the main priorities of Manufacturing-X from the outset and is promoted by international industry bodies such as CESMII (USA), RRI (Japan), KOSMO (Korea), NGen (Canada), and several European initiatives [9].

Catena-X [10] is the first global data ecosystem project that aims to create a standards-based data ecosystem for the automotive industry and provide network-ready applications. It is fully operational with the operating company Cofinity-X [11]. Catena-X focuses on use cases that support the digitalization of the automotive supply chain, i.e., it addresses a horizontal data ecosystem.

Factory-X

Factory-X [12] is the largest Manufacturing-X project and aims to become the leading project targeting industrial manufacturers and factory outfitters. It extends the entire scope of the data economy vertically, from the horizontal supply chain down to the shop floor. Factory-X is building a standardized, open, and federated digital ecosystem for Factory Outfitters and Operators, delivering solutions that leverage the concepts of Platform Industrie 4.0, such as the AAS standard and many other existing standards. Factory-X focuses on 11 dedicated industrial use cases that extend the existing supply chain-oriented Catena-X use cases and add vertical use cases to integrate shop floor operations. Data trustworthiness, data sovereignty, and data interoperability have been identified in the context of Factory-X as the pivotal challenges for data sharing and usage of data in the European market and beyond [13], so that owners or manufacturers retain control over their (specific) knowledge.

3. Challenges

Industrie 4.0 is a development that involves all stakeholders in industrial manufacturing. The upcoming developments are:

- Value focus
    - Focus on creating values from digital services in all aspects.
- Data share focus
    - Overcoming reluctance to share data about products and processes for fear of losing intellectual property, competitive advantage, or negotiating power.
- Infrastructural focus
    - **Silos:** Failure to bridge (internal) silo solutions.
    - **Lack of scaling** especially for SMEs. Risk and costs are often unsustainable for smaller companies.
    - **Complexity and heterogeneity:** Integration of people, machines, devices, and systems throughout the value chain involves many stakeholders often with their own "standards" as well as real investments.

Manufacturing-X has set itself the task of addressing these issues and providing answers. The main goal is to establish an open data ecosystem across industries. Crucial factors for success are an inclusive approach that actively involves industry representatives, associations, leading companies and SMEs, as well as support from the government. To counteract the reluctance to share data, establishing an open and trusted data ecosystem enables access to relevant data while preserving the data owner’s data sovereignty.

Silos are circumvented by use cases that connect companies within an industry, but also in neighboring industries, and serve as a blueprint for all stakeholders to tackle infrastructural challenges. The heterogeneity and complexity of manufacturing technology are addressed through open-source principles, industry standards and architectures such as AAS, OPC-UA and others. Access to Manufacturing-X must be as simple as connecting to any cloud-based network to counteract scaling issues.

In summary, it can be said, industry embarks on a similar path to science with the FAIR Principles [14] and the open science movement. But how will the seamless exchange of data in an open data ecosystem work across industries? Specifically, how will the underlying shared technological base layer as well as the regulatory framework and standards (Fig. 1) be implemented in reality? The Factory-X Kernel Systemic approach for Manufacturing-X paves the way for the future.

To some extent, this follows the Canonical Workflow Frameworks for Research (CWFR) initiative [15], which promotes the idea that scientific projects can be unique and outstanding but follow similar recurring processes and workflows and can thus be considered canonical. Hence, this enables workflow technology (e. g. GALAXY) with self-documenting workflow scripts to automate recurring processes. The applications tested in the CWFR special issue of Data Intelligence [16] in 2022 could serve as a blueprint for a canonical approach in the industry. The idea of the Manufacturing-X program, as formulated in Fig. 2 below, seems similar.

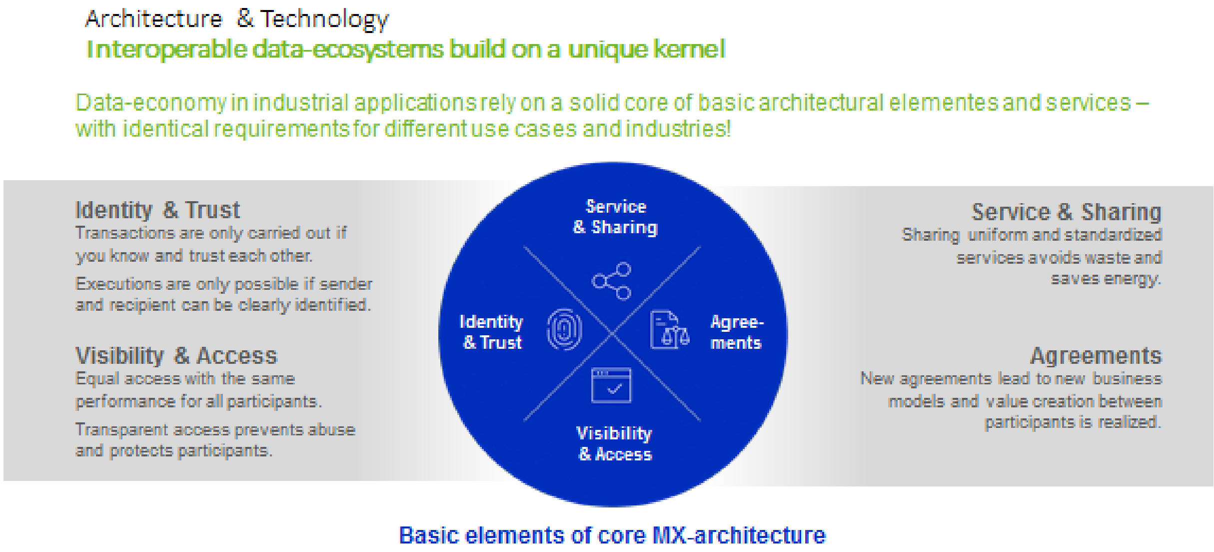

Figure 2. *Basic elements of core Manufacturing-X architecture [17]*

Figure 2 shows the basic elements of the Factory-X kernel architecture. The following section shows if and how FDOs can meet these requirements.

4. Dataspaces: FDOs as glue

The Manufacturing-X program addresses the topic of data exchange within and across industrial data ecosystems, i.e., the internal integration involving all industrial partners, including SMEs.

4.1 FDOs meet Manufacturing-X requirements?

As containers, FDOs can serve purposes both within and between data spaces. For the evaluation of the extent to which FDOs meet the requirements of Manufacturing-X, it is necessary to distinguish between three areas: (a) concept, (b) practical characteristics, (c) concrete adaptability in terms of rights, metadata and their practical implementation.

(a) In terms of concept and standardization, FDOs build on the work of the FDO Forum and its many partners. FDOs are a simple concept with few core criteria. To create, update, and retrieve digital objects, the DONA Foundation has released version 2.0 of the Digital Object Interface Protocol (DOIP) [18]. It is simple and efficient as the text-based TCP/IP protocol and promises to become the gold standard for DO exchange [19]. This means that FDOs and DOIP comply with Manufacturing-X requirements.

In terms of (b) practical implementation and (c) adaptation, a range of FDO flavors exist. For SMEs, RO-Crates [20] for example, can serve as lightweight solutions that have already been adapted in areas that overlap with industry, e.g., medical informatics [21]. They have proven their efficiency within and across industry sectors and their adaptability, e.g., for rights management.

Here lies the main advantage of FDOs and DOIP: they are simultaneously beneficial and compatible with industry, the public sector and academia. As a side effect, they support the increasing number of cross-sector collaborative projects and the impending industrialization of research and science.

4.2 GIDS Collaboration - What is in it for industry?

Manufacturing-X can not only lead to the convergence of industrial data spaces at the European and international level by using the guidelines for the DOIP and the DOA outlined by the FDO Forum but can also serve as a blueprint for the implementation of GIDS with stakeholders from Industrie 4.0, Science and Government 4.0, i.e., the digitalization of public administration and the automation of work processes in the public sector. GIDS can also be used to comply with the European data strategy [22] that require FAIRification of data not only for science but also in industry and the public sector. GIDS also enables to cross data spaces, thus FDOs can be used not only within data spaces but also across data spaces.

The overarching challenge is interoperability at all levels and layers. FDOs are a prerequisite for this. Another benefit of the FDO concept is that there are or can be several interoperable implementation options, so users are not limited to one FDO implementation version. Different needs and resources can be satisfied. FDOs enable agreement to be reached on the lowest common denominator for standardization. Participation in GIDS is also in the industry's own interest, as the areas are increasingly overlapping and are interlinked, e.g., in collaborative projects. The FDO One Project [23] has already implemented an initial integration between the joint simple-to-realize FDO layer and the more complicated EDC connector layer, which is used to control data usage exemplary in Catena-X [10] and in the Mobility Space domain [24], i.e., their solution shows the multi-layer reality of GIDS.

Using the basic idea of CWFR, a semi-automated workflow [25] with RO-Crates [26] is also possible to seamlessly integrate tools and software. For industry and beyond, this opens up new opportunities.

Manufacturing-X can learn from the FDO community to accelerate development and ensure common standards. On the other hand, Manufacturing-X can leverage its experience with stakeholder engagement, use its network of institutions, companies and government actors, show how to deal with different purposes and sizes (OEMs as well as SMEs), and use its knowledge of rights and Digital Object Asset Administration Shells.

5. Conclusion and outlook

Manufacturing-X is successful for the industrial sector because it integrates all relevant stakeholders internationally from day one. Manufacturing-X now faces the challenge of creating interoperability for OEMs, suppliers, shop floors, machines, and humans within and between industrial data ecosystems and connecting them with GIDS. FDOs and DOIP are the appropriate instruments for this, and they must be jointly designed, standardized, tested and implemented by industry, science, and the public sector. The development of Manufacturing-X can thus serve as a blueprint for the involvement of all stakeholders to make GIDS a sustainable reality for entirely new business models, efficient research workflows, and Government 4.0.

Data availability statement

Not applicable.

Underlying and related material

Not applicable.

List of abbreviations

Abbreviation	Explanation
AAS	Asset Administration Shell
BMWK	German Federal Ministry for Economic Affairs and Climate Protection
CESMII (USA)	The Smart Manufacturing Institute
DOA	Digital Object Architecture
DOIP	Digital Object Interface Protocol
EDC	Eclipse Dataspace Components
KOSMO (Korea),	Korean Smart Manufacturing Office
LNI 4.0	Labs Network Industrie 4.0
NGen (Canada)	Next Generation Manufacturing Canada
OEM	Original Equipment Manufacturer
OPC UA	Open Platform Communications-Unified Architecture
OT	Operational Technology
RRI (Japan),	The Robot Revolution & Industrial IoT Initiative
umati	universal machine technology interface

Author contributions

Conceptualization (DR, AS, CB, DB, PW); Data curation (N/A); Formal Analysis (N/A); Funding acquisition (N/A); Investigation (N/A); Methodology (N/A); Project administration (N/A); Resources (N/A); Software (N/A); Supervision (N/A); Validation (N/A); Visualization (N/A); Writing – original draft (DR, AS, CB, DB, PW); Writing – review & editing (DR, AS, CB, DB, PW).

Competing interests

The authors declare that they have no competing interests.

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