D2.2 – Digital Models and Ontologies

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ABSTRACT	The main objective of deliverable D2.2 is to collect all the recognised Data Models and Ontologies standards, describe them and categorise them in order to know the state-of-the-art of the technologies that will be used in i4Q Solutions implementation, that is, the technologies that will define the formats for the digital representation of the data through the different tools and solutions of the i4Q project. In turn, grouped by functional aspects, the technologies are aligned with the RAMI 4.0 reference architecture, which will facilitate the interoperability, exchange and processing of data. The most relevant outcome is to establish the basis for the specification of the data models and ontologies that will drive the collection, flow and exchange of digital data between the different i4Q tools and platforms.		

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ABBREVIATIONS/ACRONYMS

AI	Artificial Intelligence
API	Application Programming Interface
B2MML	Business To Manufacturing Markup Language
BDA	Big Data Analytics
CAEX	Computer Aided Engineering Exchange
CNC	Computer Numerical Control
COLLADA	Collaborative Design Activity
CPM	Continuous Process Monitoring
CPQ	Continuous Process Qualification
DEM or DEMO	Demonstrator
DLT	Distributed Ledger Technologies
EDQ	Enterprise Data Quality
EFFRA	European Factories of the Future Research Association
FMI	Functional Mock-up Interface
FMS	Factory Management System
ID	Identifier
IEEE	Institute of Electrical and Electronics Engineers
IIRA	Industrial Internet Reference Architecture
IMSA	Intelligent Manufacturing System Architecture
IOT	Internet of Things
ISO	International Organization for Standardization
IT	Information technology
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
MASON	Manufacturing's Semantics Ontology
MDA	Manufacturing Data Analytics
MDC	Manufacturing Data Consistency
MDI	Manufacturing Data Integrity

MDV	Manufacturing Devices & Virtualisation
MES	Manufacturing Execution System
ML	Machine Learning
MQA	Manufacturing Quality Assurance
MQR	Manufacturing Line Qualification and Reconfiguration
OPC	Object Linking and Embedding for Process Control
OPE	Overall Production Effectiveness
OT	Operational Technology
PKI	Public Key Infrastructure
PLC	Programmable Logic Controller
PPQ	Process Performance Qualification
PSL	Process Specification Language
QC	Quality Control
QCM	Quality Control Manager
RA	Reference Architecture
RAMI4.0	Reference Architectural Model Industry 4.0
REST	Representational State Transfer
RIDS	Reliable Industrial Data Services
SAS	Statistical Analysis System
SIMPM	Semantically Integrated Manufacturing Planning Model
SOTA	State-Of-The-Art
SQL	Structured Query Language
SSP	System Structure and Parameterization
TCP	Transmission Control Protocol
TRL	Technology Readiness Level
TSN	Time-Sensitive Networking
VRM	Value Road mapping method
WSN	Wireless Sensor Network
ZDM	Zero-Defects Manufacturing

Executive summary

This document collects the preliminary research to define the formats used for the digital representation of data managed across the different tools and solutions of the i4Q project.

The objective is to align the formats used for the distribution and storage of data generated during supply chain processes, particularly in manufacturing and maintenance operations as they are strongly connected to manufacturing quality. The consortium has identified a set of well-known standards models and ontologies adopted in the manufacturing domain, such as B2MML, AutomationML, CAEX, PLCOpen, COLLADA, MTConnect, MIMOSA and more. This document analyses the different specifications and based on these standards, proposes an alignment with the reference architecture and a set of general guidelines and action points to ease data interoperability, exchange and processing.

The main objective is that this document sets the basis for the specification of the data models and ontologies that will drive the flow and exchange of digital data across different tools and platforms.

Along with a deep SOTA analysis this document will provide the interoperability specification to be used while defining the different viewpoints of the i4Q Reference Architecture, as well as during the implementation phase in the following work-packages.

Document structure

Section 1 - Introduction: It is described the main objective of this document, which is to characterize Data Models and Ontologies used in i4Q Solutions, and how to achieve that characterization. It also describes the functional aspects, that will allow to classify them, and then describes the criteria for Benchmarking and how to evaluate them.

Section 2 - State-of-the-Art: It reviews 20 of the most important technologies that can be used in i4Q solutions, from its Description to know each data Model, State and Maturity to know its reliability, EU Projects that validate its suitability and Professional Tools for its implementation.

Section 3 - Alignment: In this section, by means of a table, it is highlighted for each Data Model which functional aspects are covered in the i4Q reference architecture, such as Control, Operations, Information, Application and Business.

Section 4 - Benchmarking: Candidate solutions that cover the same functional domain are benchmarked according to the following criteria, Coverage, Maturity/Reach, Usage Complexity and, Integration and deployment complexity.

Section 5 - Interoperability Guidelines: General interoperability guidelines based on the results of the alignment, the benchmarking and the information regarding i4Q Solutions and pilot use cases at the time of writing.

Section 6 - Liaison with on-going activities: Description of on-going projects and standardisation activities that might be relevant for the interoperability of i4Q Solutions.

Section 7 - Action Plan: Concrete actions to be taken in different tasks to promote interoperability based on the results of the analysis.

1. Introduction

The main objective of this deliverable is to describe the baseline data models, ontologies and interoperability guidelines, defined to manage the digital representation of data across the different i4Q solutions. The focus is to foster interoperability, facilitate data exchange, and data processing, both between i4Q solutions as well as with other connected systems and services.

More specifically, based on the state-of-the-art analysis below, the partners have identified data models and ontologies in the following categories:

- **Open Automation:** Models and ontologies to support the digital representation of manufacturing assets, and the exchange of operational data, from design to operations.
- **Vertical Integration:** Models and ontologies to support the integration of OT and IT systems.
- **Open Data:** Models and ontologies to model open data interfaces and support the open exchange of data between distributed systems.
- **Open Analytics and AI**: Models and ontologies to support the modelling and distribution of analytic functionalities including machine learning.

The candidate solutions are first mapped into the following functional domains of the i4Q reference architecture, according to the IIRA architectural models:

- Control:
  - **Sensing:** models and ontologies for the representation of sensor data
  - **Actuation:** models and ontologies for the representation and dispatching of commands to actuators, as well as the implementation in controllers, both hardware and software.
  - **Communication:** models and ontologies to support the exchange of messages, the connectivity, and the Quality of Service between sensors, actuators, as well as other OT and IT infrastructure components, such as gateways, controllers, switches, or routers.
  - **Entity Abstraction:** models and ontologies for the virtual representation and abstraction of the different physical infrastructure components (sensors, actuators, controllers) and their relationships, including the semantics of the messages between system elements.
  - **Modelling (edge analytics):** models and ontologies to support the understanding of the states, conditions and behaviour of the state of the system, that generally need to be evaluated close to the sensor, including pre-processing of raw sensor data (time series alignment, harmonisation, or transformation into higher-level information).
  - **Asset management:** models and ontologies to support lifecycle management operations of the underlying components of the control system (onboarding, configuration, system, software/firmware updates).
  - **Execution**: models and ontologies for the execution of the control logic according to control objective.

- Operations:
  - **Provisioning and Deployment**: Models and ontologies to support asset commissioning and de-commissioning (configuration, onboarding, registration, and asset tracking, as well as to deploy and retire assets from operations).
  - **Asset Management**: Models and ontologies that support assets management, issuing management commands to control systems, and from the control systems to the assets in which the control systems are installed, and in the reverse direction enable the control systems and the assets to respond to these commands.
  - **Monitoring and Diagnostics**: Models and ontologies to enable the detection and prediction of occurrences of problems.
  - **Prognostics**: Models and ontologies to support analytic functions required to make predictions from the control systems operational data.
  - **Optimization**: Models and ontologies to support the definition of optimization functions required to improve operations.
- Information:
  - **Data Ingestion:** Models and ontologies for ingesting sensor and operational states from all domains, data cleansing, including online streaming
  - **Quality of data:** Models and ontologies to support quality-of-data processing functions (data cleansing, filtering, de-duplication, etc.),
  - **Syntactical transformation:** Models and ontologies to support syntactical transformation of data and the definition of syntactical transformation rules (e.g., format and value normalization),
  - **Semantic transformation:** Models and ontologies to support semantic functions (semantic assignment, context injection and other data augmentation processing based on metadata (e.g., provisioning data from the Operations Domain) and other collaborating data set.
  - **Data persistence and storage:** Models and ontologies to support persistence and storage (e.g., for batch analysis).
  - **Data distribution:** Models and ontologies to support data distribution (e.g., for streaming analytic processing).
- Application:
  - **Logic and rules:** models and ontologies for implementing specific application functionality that is required for the use cases under consideration.
  - **APIs and UIs:** models and ontologies for exposure of the application capabilities as APIs for other application use or User Interfaces for humans use.
- Business:
  - **Business**: models and ontologies to the integration of business functions that enable end to end operations including, Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), Product Lifecycle Management (PLM), Manufacturing Execution System (MES), Human Resource Management (HRM) functions.

- **I4Q vertical**: models and ontologies to support i4Q as a vertical, specifically designed to support the definition of process quality, product quality, and manufacturing line qualification.

Once that the candidate solutions are aligned to this functional model, the different alternatives in each category that cover the same functional domain are benchmarked according to the following criteria.

- **Coverage**: Capability to model the different use cases (pilots). The positive or negative evaluation is related to the fitness, appropriateness, and usefulness of the application of a technology in the different pilots from the project.
- **Maturity/reach**: Level of maturity and market reach. A positive evaluation means that the model or ontology is widely adopted as an industry standard and that there is a range of commercial solutions available.
- **Ease of use**: An estimation of the usage complexity, when applicable estimated from the number of classes or entities and their corresponding attributes involved in coverage. A positive evaluation means that the model or ontology is easy to use in the pilot use cases
- **Integration and deployment complexity**: Availability of open-source tools, liaison documents and companion specifications to support the specification, instantiation, implementation, and deployment of data models in the pilot use cases. A positive evaluation means that it is not complex to integrate or deploy.

The analysis is performed according to the following definitions:

- **'+'** symbol means a positive evaluation of a specific criteria.
- **'-'** symbol means negative evaluation of such criteria.
- **'NA'** means 'not applicable' as such criteria does not have direct relationship with the model or ontology benchmarked.

Moreover, to provide a more quantitative benchmarking, the analysis will use 1, 2 or 3 '+' or '-' symbols to quantify the degree of positiveness or negativity of such criteria in the assessed technology as it is shown in Table 1.

+	++	+++
Slightly	Moderately	Very
-	--	---
Slightly little	Moderately little	Very little

Table 1. Benchmarking notation

From the analysis of the benchmarking results, this document collects a set of actionable recommendations, including the use of data models and ontologies, to guide data representation and exchange in the i4Q ecosystem. It also develops a liaison strategy with on-going initiatives to further promote interoperability.

The rest of the document is structured as follows. Section 2 contains the state-of-the-art analysis of the different candidate solutions. Section 3 contains the alignment of standards, data models and ontologies with the identified domains. Section 4 contains the results of the benchmark, Section 5 the final conclusions and interoperability guidelines, and Section 6 the Liaison with on-going activities.

2. State-of-the-Art

2.1 Category - Open Automation

2.1.1 Field Device Integration

2.1.1.1 Description

In today's automation systems many field devices from many different manufacturers have to be integrated, resulting in effort for installation, version management and device operation. The Field Device Integration (FDI) relieves the worker from all those inconveniences. The FDI is a standard device integration technology (Gunzert, 2015) based on the IEC 61804 standard and managed by the FDI organization. The IEC 61804, in turn, is a standard that defines the Electronic Device Description Language (EDDL), a generic language for describing the properties of automation system components. The EDDL describes device parameters and their dependencies, device functions, graphical representations (i.e., menus), etc.

The primary objective of FDI is to dramatically simplify software installation, configuration, maintenance and management of field instruments and host systems. FDI brings standardization to the packaging and distribution of all software and tools necessary to integrate a device with a host system. All registered FDI devices have an associated FDI Device Package (Gunzert, 2015). An **FDI Device Package** is a single software module that contains all drives, interfaces, certificates and documentation for managing the device within the system.

FDI Device Packages are imported by **FDI hosts**, allowing users to operate the device. An FDI host can be a stand-alone software component, an integrated software component in a distributed control system or a software component with a client server architecture. An FDI host typically consists of an FDI client, an FDI server and one or more FDI communication servers.

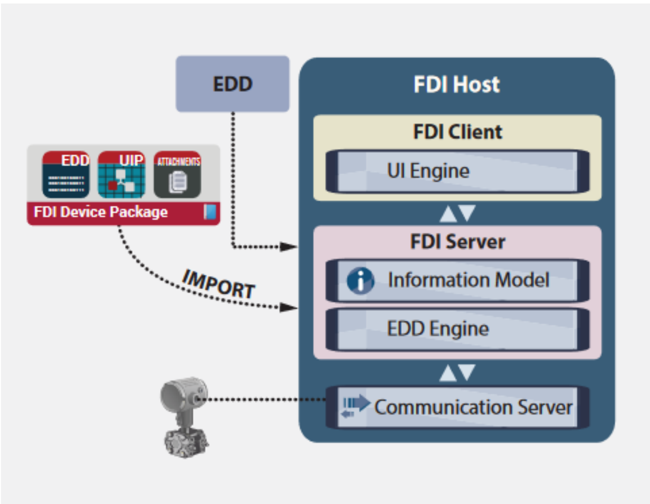

Figure 1. Field Device Integration diagram[1]

[1] https://www.fieldcommgroup.org/sites/default/files/technologies/fdi/FDI%20Brochure.pdf

- **FDI server:** it contains the FDI information model. The information model describes the topology of automation systems. Therefore, it describes the devices of the system as well as the communication networks, including their properties, relationships and the operations that can be performed on them, see **Figure 2**. The Information model is mainly based on OPC UA for Devices specification; in fact, most of the OPC UA for Devices model has been driven by FDI requirements (Schulz & Gitzel, 2013). The information model also manages the FDI clients' UIPs and UIDs.
- **FDI client:** it contains the User Interface Plug-in (UIP) or the User Interface Description (UID). The UIP is a software component that adds a specific feature to an existing computer program, and the UID is the specific design of the visual aspect of a product. In resume, the FDI client provides human-readable information for device parametrization.

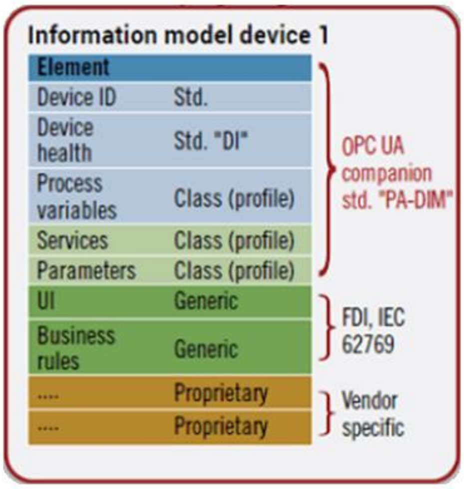

Figure 2. Field Device Integration information model example[2]

- **Communication server:** it specifies the elements that implement the communication capabilities. The communication Server supports standard protocols like HART, PROFIBUS, PROFINET and FOUNDATION Fieldbus.

All FDI is described in the standard IEC 62769.

2.1.1.2 State and maturity

The FDI is specified in the IEC (International Electrotechnical Commission), a well stablished standardization organization for electric, electronic and related fields.

2.1.1.3 EU projects

Acronym*	GA	Solution	Description
COSMOS	246371	Cost-driven Adaptive Factory based on	The main objective for COSMOS is the design/development/implementation of a control system for factory management with a flexible,

[2] https://www.controlglobal.com/articles/2018/software-eases-field-device-integration/

Acronym*	GA	Solution	Description
		Modular Self-Contained Factory Units	modular and evolvable automation approach which will permit to increase the assembly factory productivity by 20% without losing flexibility, focused on wind turbine assembly process although the solution will be suitable for other sectors.

**The acronym's name is a link to the web page of the EU project solution.*

Table 2. Field Device Integration EU projects

2.1.1.4 Professional tools

As described in previous subsections, the FDI can be found alongside HART, PROFIBUS, PROFINEL and FOUNDATION Fieldbus protocols (which entails the 90% of industrial process automation), as well as alongside OPC UA.

If first registered in the FDI organization, the FDI can be implemented in any of the registered devices (sensors, actuators, regulators, etc.), therefore, all the registered devices' custom software can be considered to be a FDI's professional tool. The whole registered software and hardware list can be found in the FDI's official web page. Some examples are displayed in **Table 3**.

Solutions*	Description
IGP10S-F Advanced Performance	A Schneider Electric's gauge pressure transmitter.
AWT210	An ABB's analytical water transmitter.
2140 Level Detector	An Emerson Automation Solutions' level detector.
373X-5	A SAMSON AG's electropneumatic positioner.
954 SMARTSERVO FLEXLINE	A Honeywell International smart level servo

**The solutions' name is a link to the web page of the company's solution developer.*

Table 3. Field Device Integration Professional tools

2.1.2 OPC UA

OPC Unified Architecture (OPC UA) is a machine-to-machine communication protocol for industrial automation developed by the OPC Foundation. OPC UA is based on OPC (OLE for Process Control), which in turn, is based in OLE (Object Linking and Embedding). It all started in non-industrial systems with the need to use one application's objects in other applications. Which is to say: it all started because of the lack of interoperability between applications in non-industrial systems. The standard OLE mended that lack of interoperability. The standard OPC upgraded the OLE for industrial systems, archiving the communication of real-time plant data between control devices from different manufacturers. And finally, the OPC UA standardized and upgraded the OPC to meet the emerging needs of industrial automation (Hannelius et al., 2008).

OPC technologies were created to allow information to be easily and securely exchanged between diverse platforms from multiple vendors and to allow seamless integration of those platforms without costly, time-consuming software development.

2.1.2.1 Description

OPC UA is a **communication** protocol which focusses on communication between industrial equipment and systems for data collection and control. Hence, it is not tied to one operating system or programming language (cross-platform). The communication is based on the client-server and service-oriented architecture (SOA) (Leitner & Mahnke, 2006). In the client-server architecture one or more devices (the clients) demand resources and services form one or more devices (the servers). And in the SOA, the services are provided by the server as application components, making the service a black box, meaning that the client does not have to be aware of the service's inner workings.

The OPC UA **specification** is a multi-part specification and consists of the following parts: Concepts, Security Model, Address Space Model, Services, Information Model, Mappings, Profiles, Data Access, Alarms and Conditions, Programs, Historical Access, Discovery and Global Services, Aggregates and PubSub.

OPC UA supports **two protocols**, which are visible to application programmers only via changes to the URL. The protocols are the binary protocol opc.tcp://Server and the Web Service protocol http://Server. Otherwise OPC UA works completely transparent to the API.

The **binary protocol** offers the best performance/least overhead, uses a single arbitrarily choosable TCP port for communication easing tunnelling or easy enablement through a firewall, takes minimum resources (no XML Parser, SOAP and HTTP required, which is important for embedded devices) and offers best interoperability (binary is explicitly specified and allows fewer degrees of freedom during implementation). The **Web Service (SOAP) protocol** is best supported from available tools, e.g., from Java or .NET environments, and is firewall-friendly, using standard HTTP(S) ports. Binary is supported by all implementations, while only .NET implementation supports SOAP.

2.1.2.2 State and maturity

OPC UA is considered as the data exchange standard for safe, reliable, manufacturer- and platform-independent industrial communication. It is a mature standard that is managed by the OPC Foundation. Today, there are more than 4,200 suppliers who have created more than 35,000 different OPC products used in more than 17 million applications.

2.1.2.3 EU projects

There is a significant amount of EU projects in which device communication with OPC UA is one of the tasks, or in which a standard or protocol is developed based on OPC UA. Some examples of those projects are displayed in **Table 4**.

Acronym*	GA	Solution	Description
COSMOS	246371	Cost-driven Adaptive Factory based on Modular Self-Contained Factory Units	The main objective for COSMOS is the design/development/implementation of a control system for factory management with a flexible, modular and evolvable automation approach which will permit to increase the assembly factory productivity by 20% without losing flexibility, focused on wind turbine assembly process although the solution will be suitable for other sectors.
CLAFIS	604659	Crop, Livestock and Forests Integrated System for Intelligent Automation, Processing and Control	(CLAFIS) will develop and demonstrate a pre-commercial intelligent integrated solution prototype based on a cross platform OPC unified architecture (OPC UA) specification entitling standards and related technologies for communication between automation systems and IT systems in farms and forest related process. The project is centred on a Use Case demonstrator involving a complete process sequence of a smart seeding, spraying and harvesting for grass/grains/trees
NI2S3	225488	Net information integration services for security systems	The key objective of the NI2S3 project is to research and implement a reference methodology for developing security systems based on network enabled capabilities (NEC) information and integration services (I2S) for CIs. The security systems must be capable to collect and process information from many heterogeneous sources in order to build up or improve the situation awareness of CIs and to enable the decision making.
LAY2FORM	768710	Efficient Material Hybridization by Unconventional Layup and Forming of Metals and Composites for Fabrication of Multifunctional Structures	LAY2FORM will create a new cost-effective multistage manufacturing platform based on flexible machinery concepts, cognitive automation, inline monitoring and inspection, as well as simulation and modelling, enabling the efficient integration of unconventional technologies (laser and ultrasound) in established composites-based processes, namely tape-laying and hot-forming, to enable the production of multifunctional 3D hybrid parts from thin layered metals and thermoplastic-matrix composites.

**The acronym's name is a link to the web page of the EU project solution.*

Table 4. OPC UA EU Projects

2.1.2.4 Professional tools

This communication standard is supported by many industrial partners that develop or use this protocol for the communication of the various devices that form their systems. Therefore, this standard's professional tool is always dependent on the element registered[3] in the OPC UA Foundation as can be seen in **Figure 3**. Some examples of the registered elements are displayed in **Table 5**.

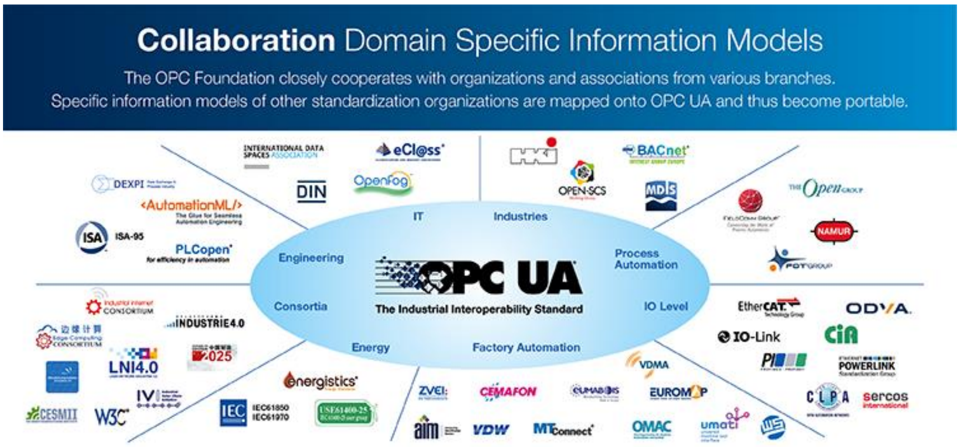

Figure 3. OPC UA collaboration Domain Specific Models[4]

Solutions*	Description
LabVIEW OPC UA API	National Instruments' API for creating OPC UA clients and server in the LabView software.
SIMATIC NET OPC Server	Software for the creation of OPC servers in Siemens AG's software/hardware.
Discovery Module	Software for creating OPC UA servers in Microsoft Azure IoT Edge.
Omron NJ5 Machine Automation Controller	Omron's PLC.
EK9160 | IoT Bus Coupler	Beckhoff Automation's communication module.

**The solutions' name is a link to the web page of the company's solution developer.*

Table 5. OPC UA Professional tools

[3] https://opcfoundation.org/products
[4] https://opcfoundation.org/markets-collaboration/

2.1.3 MTConnect

MTConnect is a manufacturing technical standard to retrieve process information from numerically controlled machine tools. MTConnect is a protocol designed for the exchange of data between shop floor equipment and software applications used for monitoring and data analysis.

2.1.3.1 Description

MTConnect is referred to as a read-only standard, meaning that it only defines the extraction (reading) of data from control devices, not the writing of data to a control device. Freely available, open standards are used for all aspects of MTConnect. Data from shop floor devices is presented in XML format, and is retrieved from information providers, called Agents, using Hypertext Transfer Protocol (HTTP) as the underlying transport protocol. MTConnect provides a RESTful interface, which means the interface is stateless. No session must be established to retrieve data from an MTConnect Agent, and no logon or logoff sequence is required (unless overlying security protocols are added which do). Lightweight Directory Access Protocol (LDAP) is recommended for discovery services.

The MTConnect standard (ANSI/MTC1.4-2018) offers a semantic vocabulary for manufacturing equipment to provide structured, contextualized data with no proprietary format. With uniform data, developers and integrators can focus on useful, productive manufacturing applications rather than translation. Data sources include: machine tool, production equipment, sensors and sensor controllers, and other factory hardware.

Applications that consume MTConnect data provide more efficient operations, improved production optimization, and increased productivity. Scalable system architectures depend on standards. MTConnect provides domain-specific vocabulary and data models, is extensible, and integrates with other standards by design.

MTConnect is used on more than 50,000 devices in over 50 countries, 11 years since first release, 1000’s of software solutions and developed by over 300 machine builders, integrators, and end-users.

2.1.3.2 State and maturity

The MTConnect Institute, standard development organization for MTConnect, announced the release of Version 1.6.0 of the MTConnect standard on September 2020, the world’s only free, open semantic vocabulary for discrete manufacturing. This version includes:

- New data items and information models for additive manufacturing including high frequency data display, new data types and subtypes.
- Many new data items for machine tools including execution states, work offsets, program header subtypes, machine specifications, voltage and amperage.
- Expanded data items for robots including path orientation, coordinate systems, and joints and axes.
- Editorial corrections and refined information modelling.

2.1.3.3 EU projects

Acronym*	GA	Solution	Description
STEPMAN	286962	Computer aided design and manufacturing processes	Development of a STEP and STEP-NC standard based integrated product lifecycle management solution to increase the competitiveness of European machine tool manufacturing SMEs.
PLANTCockpit	260018	Production Logistics and Sustainability Cockpit	Smart Factories: ICT for agile and environmentally friendly manufacturing.

**The acronym's name is a link to the web page of the EU project solution.*

Table 6. MTConnect EU projects

2.1.3.4 Professional tools

Solutions*	Description
Manufacturers and software developers	The MTConnect C++ Agent is free, open-source software. Community developed and maintained. A live example instance of the C++ Agent is provided by the National Institute for Standards and Technology (NIST) for testing, development, and educational purposes.
Developers, system architects, and process/systems engineers	SysML model of MTConnect
XML Schema Definition (.XSD) files for validating MTConnect implementations	MTConnect XML Schema Repository. All versions.

**The solutions' name is a link to the web page of the company's solution developer.*

Table 7. MTConnect Professional tools

2.1.4 PLCopen

PLCopen was founded in 1992 just after the worldwide programming standard IEC 61131-3 was published. The IEC 61131 was published to give solution to the highly heterogeneous control market of that time, market in which a significant number of PLC programming methods coexisted. Therefore, the standard's objective was to define a set of rules with which PLC programming software could be defined. PLCopen's objective, in turn, is to improve industrial automation' efficiency creating technical specifications and implementations based on IEC 61131-3.

PLCopen, in fact, is an independent organisation in which PLCopen members and end user altogether create the mentioned specifications with the objective of reducing costs in industrial engineering through software standardization. The outcomes of the mentioned task are application libraries, harmonized language conformity levels and engineering interfaces for exchange (Kim et al., 2013).

2.1.4.1 Description

PLCopen member's and end user's tasks fall into one of the following topics:

- Logic

The PLCopen's logic or basic elements of programming (language syntactic and semantic rules) are provided by the standard IEC 61131-3: Programming Languages. The standard's Programming Languages are independent from specific dialects but, still based on known methods such as the textual programming languages Instruction List (IL) and Structured Text (ST); the graphical programming languages Function Block Diagram (FBD) and Ladder Diagram (LD); and the structuring tool Sequential Function Chart (SFC). These languages are used in PLCs, embedded controls and industrial PCs.

Today, IEC 61131-3 is a highly accepted programming standard, hence, many industrial software and hardware companies offer products based on this standard, which in the end, are used in many different machinery and other application fields.

- Motion control

In the past, motion control required unique software to be created for each application, even if different application's functions were the same. Therefore, motion control was added to the PLCopen topic's collection with the aim of creating standard application libraries that are reusable for multiple hardware platforms. This way the programming is less hardware dependent, the reusability of the application software is increased, the cost involved in training and support is reduced, and the application becomes scalable across different control solutions. Due to the data hiding and encapsulation, the standard's application libraries are usable on different architectures, ranging from centralized to distributed or integrated to networked control.

- Safety

Together with an external safety related organization, PLCopen defined safety related aspects within the IEC 61131-3 development environments (Soliman & Frey, 2011). With this, the safety aspects can be supported by a dedicated software tool, which is integrated into the software development tools. As such, it combines logic and motion application development with its related safety aspects, abstracting the safety programming task and facilitating the programmer's work.

The safety standardization reduces certification time and costs by relevant organizations.

- Communication

Initiatives like Industry 4.0, Smart Factories, industrial Internet of Things, and others, have communication as key element. These initiatives are constituted of big, interconnected device systems, therefore efficient data transfer between devices (sensors, actuators, intelligent systems, …) and security has become more and more important.

To achieve those two objectives, PLCopen and OPC Foundation have joined forces to provide a solution to make data transfer's programming, installation, maintenance and update easier. The solution is based on the OPC UA technology, using OPC UA communication as a standard of communication for industrial environment. Hence, the

PLCopen's software objective is to facilitate the use of OPC UA communication in any PLC, industrial PC or embedded system's programming software.

- XML Exchange

The XML Exchange was not intended as a standard but, it was originated from users' necessity to exchange their programs, libraries and projects between development environments. The XML Exchange is an open interface used by different kinds of software tools to transfer the information that is on the screen between platforms. The screen information may be textual information or graphical information and is programmed in XML language.

XML stands for eXtensible Markup Language, it is a markup language that defines a set of rules for encoding documents in a format that is both human-readable and machine-readable.

- Certificate

The last PLCopen members' task is the certification of programming systems that are IEC 61131-3 compliant (Logic) and in compliance with the requirements stated in the PLCopen Motion Control, Safety, OPC UA and XML specifications.

2.1.4.2 State and maturity

PLCopen is a well stablished organization that develops software based on the most commonly used standard (IEC 61131) for PLC's, industrial PC's and embedded system's programming. It has joined forces with Microsoft for the data transfer task (OPC UA). Its software can be found in the programming software of a great deal of companies (Siemens, Mitsubishi Electric, Omron, Rockwell Automation, Siemens, Schneider Automation, …). Moreover, PLCopen follows market demands, developing software and standards on demand.

2.1.4.3 EU projects

Acronym*	GA	Solution	Description
PLC-PROG	243484	Improving PLC programming through a new graphical, object-oriented and brand- independent programming framework	PLC-PROG is much more than a software. It opens the way to the standardisation of program code in PLCs. Following the basis of the IEC 61131-3 Standard, PLC-Prog defines a visual language based on racks that permits the user to create complex PLC programs with simple drag and drop operations.
COSMOS	246371	Cost-driven Adaptive Factory based on Modular Self-Contained Factory Units	The main objective for COSMOS is the design/development/implementation of a control system for factory management with a flexible, modular and evolvable automation approach which will permit to increase the assembly factory productivity by 20% without losing flexibility, focused on wind turbine

Acronym*	GA	Solution	Description
			assembly process although the solution will be suitable for other sectors.

**The acronym's name is a link to the web page of the EU project solution.*

Table 8. PLCopen EU Projects

2.1.4.4 Professional tools

As said before, PLCopen develops standards and libraries for PLCs. Therefore, the professional tools that do use or are in compliance with the PLCopen's software are all the devices registered in the PLCopen organization. Some examples are displayed in **Table 9**.

Solutions*	Description
Motion library for servo drive Lexium28	Schneider Electric's Lexium28 servo drive's motion library.
Micro800 controller	Rockwell Automation's Micro800 controller's motion control library.
iQ-F Series FX5U/FX5UC/FX5UJ, GX Works3	Mitsubishi Electric's iQ-F's motion control library.
TwinCAT Motion	Beckhoff Automation's TwinCAT motion library.
Motion library for servo drive Lexium28	Schneider Electric's Lexium28 servo drive's motion library.

**The solutions' name is a link to the web page of the company's solution developer.*

Table 9. PLCopen Professional tools

2.1.5 COLLADA

2.1.5.1 Description

COLLADA —which stands for COLLAborative Design Activity— constitutes an interchange (open-standard XML) file format for storing interactive 3D models and /or 3D applications. Khronos Group, which is a non-profit technology consortium, run COLLADA. Moreover, ISO approved COLLADA, with the code ISO/PAS 17506, as a free available digital schema [5]. COLLADA is often used in 3D applications, as an interchange format. It is an open standard XML schema that is being used in order digital assets to be easily exchanged among other software applications of graphic design. This XML schema helps to store assets from other graphic applications in compatible file formats with COLLADA and thus the opportunity to easily use data without extra procedures of changing their format. The COLLADA files that define the digital assets, are files in

XML format, that have the .dae (digital asset exchange) filename extension and can indicate supplementary image files, which can be draped onto the 3D object and act as textures. COLLADA allows the export of multipatch features, thus offering the opportunity to share multiple analysis results with other applications/software. Furthermore, COLLADA file format can update 3D GIS data, e.g., buildings' data, while working together with another software, such as the SketchUp or the 3DS Max[6] software.

Khronos Group offers freely the COLLADA specification and schema, while the SCEA Shared Source License 1.0 is being used by COLLADA DOM.

From the beginning of COLLADA, many companies with graphic software collaborated with Sony, in order to create a useful and easily handled tool, accessible to a broad audience. Khronos contributors still continue their efforts and COLLADA continues to progress. Some of the very first collaborators of COLLADA were Avid Technology, Alias Systems Corporation, Autodesk, Inc., and Criterion Software. Since then, the COLLADA standard has been adopted by multiple commercial game studios and engines.

In March 2011, the COLLADA Conformance Test Suite (CTS) was released by Khronos. The function of CTS is to ensure that applications, which import and export COLLADA, follow the necessary specifications. This control can be done by allowing to these applications to test multiple example suites. In July 2012, GitHub released the CTS software, allowing for community contributions.

In July 2012, COLLADA published the ISO/PAS 17506:2012 Industrial automation systems and integration, enhancing the 3D visualization of industrial data[7].

2.1.5.2 State and maturity

COLLADA was developed at Sony Computer Entertainment, Khronos Group, by Rémi Arnaud and Mark C. Barnes[8] . Its initial release was on October 2004 and its latest release, 1.5.0 was on August 2008.

All the available versions of COLLADA are listed below:

- Version 1.0: released on October 2004
- Version 1.2: released on February 2005
- Version 1.3: released on June 2005
- Version 1.4.0: released on January 2006; extra features were added in this version, such as morph targets and character skinning, support for OpenGL ES materials, rigid body dynamics, shader effects for many languages, e.g., Cg programming language, GLSL, HLSL. The first release of this version was done through Khronos.
- Version 1.4.1: released on July 2006; this was mainly a patch release.

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[6] https://pro.arcgis.com/en/pro-app/latest/tool-reference/conversion/an-overview-of-the-to-collada-toolset.htm

[7] https://www.iso.org/standard/59902.html

[8] https://www.khronos.org/collada/

- Version 1.5.0: released on August 2008; extra features were added in this version, such as kinematics, B-rep, and support for FX redesign and OpenGL ES. This version was formalised as ISO/PAS 17506:2012.

2.1.5.3 EU projects

Acronym*	GA	Solution	Description
EU Projects NOT FOUND			

**The acronym's name is a link to the web page of the EU project solution.*

Table 10. COLLADA EU projects

2.1.5.4 Professional tools

Solutions*	Description
Autodesk InfraWorks	Autodesk InfraWorks is a conceptual design software for civil infrastructure and can be used for modelling, analyzing, and visualizing design concepts within a real-world context.
Google Earth	Google Earth is a computer program which is mainly based on satellite imagery and it offers a 3D representation of Earth.
NASA World Wind	NASA WorldWind is an open-source virtual globe.
SketchUp	SketchUp is a 3D modelling computer program. It is used in multiple drawing applications, e.g., mechanical and civil engineering, interior design, architectural, landscape architecture, video game design and film design.
OpenSimulator	OpenSimulator is an open-source server platform, that is used in order to host virtual worlds.
Maple (software)	Maple is a multi-paradigm programming language and a symbolic and numeric computing environment.
BricsCAD	BricsCAD is a software application, designed for computer-aided design (CAD).
Mathematica	Mathematica is a new technical computing system. It covers many areas of technical computing — including machine learning, neural networks, image processing, data science, geometry, visualizations, and others.
Panda3d	Panda3D is a game engine that is used in the creation of 3D games. It includes abilities, such as graphics, audio, and other.
Ardor3D	Ardor3D is a 3D video game engine in Java language, for high performance gameplay and visualization.
Visual3D Game Engine	Visual3D Game Engine is a 3D game development tool and game engine.

Solutions*	Description
Libaries: COLLADA DOM, FCollada, ColladaMaya, ColladaMax, OpenCOLLADA, pycollada, StormEngineC.	Interchange file formats for interactive 3D applications. Reference architecture.

**The solutions' name is a link to the web page of the company's solution developer.*

Table 11. COLLADA Professional tools

2.1.6 CAEX

CAEX (Computer Aided Engineering Exchange) is a neutral data exchange format for plant engineering data, which handles heterogeneous or integrated data representations, allows hierarchical object information to be stored, and aims at interoperability.[9]

Such a plant consists of interconnected components or modules, which are stored by CAEX by means of objects. Object oriented concepts that are explicitly supported by CAEX, are the following: class libraries, encapsulation, instance hierarchies, relations, classes, inheritance, interfaces and attributes. CAEX was developed to support the exchange and validation of plant engineering models, due to their growing complexity. It can support experts during the process of plant construction. Furthermore, it is part of the AutomationML (AML) language specification, especially developed for the engineering domain in order to meet engineering requirements.

2.1.6.1 Description

CAEX is based on XML and therefore it is defined as an XML schema (.xsd file). The initial goal of developing CAEX was to fulfil the need of industries for data exchange during processes, and the establishment of a common data exchange between the control engineering tools and the engineering tools. Nevertheless, CAEX can be functional and be used to all the categories of static object information, e.g., document topologies, plant topologies, petri nets, product topologies. Besides, it can be used for non-technical applications, such as the phylogenetic trees.

CAEX combines both model-techniques and meta-model-techniques. On the one hand, the model-techniques allow object information that is common across various vendors to be stored, e.g., attributes, objects, interfaces, references, hierarchies, classes and libraries. On the other hand, the meta-model-techniques allow individual and application dependent object information to be defined, e.g., object catalogues or specific classes, and certain attribute names. CAEX is mainly considered as a static data format and it is not designed to store dynamic information. However, it can describe dynamic behaviour by defining special classes.

[9] https://www.plt.rwth-aachen.de/cms/PLT/Forschung/Projekte2/~ejwy/CAEX_IEC_62424/?lidx=1

2.1.6.2 State and maturity

In 2002 the development of CAEX was started, as a university project, at RWTH Aachen. Chair of the process control engineering was Prof. U. Epple and the project was industrially supported by ABB corporate research Ladenburg. The initial CAEX project proposal was presented and submitted to the German standardization committee DKE K941 (TC65, WG12) in 2003. Next, CAEX was published in 2004, as part of the DIN V 44366. In May 2005, CAEX was published as part of the IEC PAS 62424, after a positive international vote. The following IEC standardization step was passed in 2007, and was published as IEC 62424 CDV (Committee Draft for Voting). The final version of IEC 62424 (Ed. 1.0) was published on August 12th, 2008.

The current available version can be found as: CAEX Version 3 (Version 3).

2.1.6.3 EU projects

Acronym*	GA	Solution	Description
GOODMAN	H2020-IND-CE-2016-17	Agent Oriented Zero Defect Multi-Stage Manufacturing	**GOODMAN** project establishes the implementation of the Industry 4.0 model, in a real-world context. This is realised through the integration and conjunction of technologies at factory level and single process, in order to run measurement and quality control, data analysis and management. The final goal of this project is to improve the production efficiency of the complete system, trying to develop a production strategy that can assure high quality products, without interfering. project duration: from 01/10/2016 to 30/09/2019. Deliverable 2.2, Ontology Definition, 12/01/2017

**The acronym's name is a link to the web page of the EU project solution.*

Table 12. CAEX EU projects

2.1.6.4 Professional tools

Solutions*	Description
There are no professional tools for CAEX.	

**The solutions' name is a link to the web page of the company's solution developer.*

Table 13. CAEX Professional tools

2.1.7 AutomationML

2.1.7.1 Description

Based in XML, Automation Markup Language (AutomationML) is a data format designed to exchange and storage engineering information's data which typically exists inside a factory environment. This is the original scope where heterogeneous engineering tools co-exist and where AutomationML's objective comes in to place to interconnect broad tools landscape as an open standard and exchange information within smart devices, systems and components (Drath, 2012).

Plant components like electrical designs, mechanical plant engineering, robot control and PLC or even a motor, a screw or a valve can be described by AutomationML as objects with encapsulated information where each object can be then aggregated as a sub-set of other described objects (L. Hundt, R. Drath, 2008). By this enclosed information on each object like geometry, logic and kinematics AutomationML enables a uniform and bidirectional data exchange throughout the whole engineering process.

Through strongly typed links AutomationML comprises different standards like CAEX (IRC 62424 to implement Topology format from properties and relations of objects in the hierarchical structure. Then the Geometry and Kinematics formats are implemented with COLLADA by using the graphical attributes and dependencies between objects to support motion planning, respectively. By integrating PLCopen XML from interactions of objects and I/O connections, AutomationML can incorporate the Logic format (E. Estévez, M. Marcos, 2010).

Among the data exchange throughout the engineering process where several tool can co-exist, AutomationML can be used to exchange data between CAD system of from CAD system directly to documentation repositories.

2.1.7.2 State and maturity

The first evaluations of exchanges formats jointly done by ABB, Siemens and other institutes and partners as Karlsruhe Institute of Technology or netAllied, done at October 2006 to define and standardize the Automation Markup Language. In April 2009, an independent organization was founded and the AutomationML is available as open standard.

2.1.7.3 EU projects

Acronym*	GA	Solution	Description
SkillPro	314247	"Skill-based Propagation of ""Plug&Produce""-Devices in Reconfigurable Production Systems by AML"	(2012-2015) provides an extension of the Plug-and-Produce paradigm using knowledge about the skills of the diverse automation system components (composition and cooperation) where the production system capabilities are describes with AutomationML.
Maya	678556	Multi-disciplinary integrated simulation and forecasting tools, empowered by digital continuity and continuous real-world synchronization, towards reduced time	(2015-2018) supports the digital continuity by developing a standardized, open semantic meta-model capable to fully describe the properties and functional characteristics of the CPS simulations models based on AutomationML.

Acronym*	GA	Solution	Description
		to production and optimization	

*The acronym's name is a link to the web page of the EU project solution.

Table 14. AutomationML EU projects

2.1.7.4 Professional tools

Solutions*	Description
AML.hub	Developed by logi.cals and the CDL-Flex research laboratory, provides function for the management of integrated plant model.
COMAN	Software solution for layout based digital site management to accelerate project execution
TIA Portal v14	Siemens is expanding its engineering framework where the TIA Portal v14 brings openness to other systems

*The solutions' name is a link to the web page of the company's solution developer.

Table 15. AutomationML Professional tools

2.1.8 DIN Spec 91345 RAMI 4.0

2.1.8.1 Description

In the scope of Industry 4.0 DIN Spec 91345:2016-04 describes a standard Reference Architecture Model based on a three-dimensional layer model for Industry 4.0 under the name RAMI 4.0 (Reference Architecture Model Industry 4.0). Represents a basic architecture using a sophisticated coordinate system. From the practical point of view, RAMI 4.0 implements an important step to the Industry 4.0 journey.

Along the entire value chain – development, production, use and disposal – the technical objects called Assets under RAMI 4.0 (tangible or not) can be represented as well as all relevant aspects that detail or concern them. Thus, the objective of this standard Reference Architecture Model is to show on which level, and in which phase each industry component plays a role and where it interacts with remaining components at different levels.

When it comes to the digital representation of an asset, all those assets like machines, components, materials and even contracts and orders must be identifiable. Industry 4.0 network must be able to read an identify all the specific information related to the asset like its type. To achieve this, RAMI 4.0 introduces the Asset Administration Shell (AAS). In this sense, the Asset itself is the physical part where the Administration Shell is the digital part by storing its identification, technical and operational information during the asset's lifecycle. Therefore, the AAS provides a standardized, interface between the asset and the Industry 4.0 network.

2.1.8.2 State and maturity

The architecture reference model presented in DIN Spec 91345 is being well established that intends to standardize industry 4.0 applications.

2.1.8.3 EU projects

Acronym*	GA	Solution	Description
BOOST 4.0	780732	Governance model, for both services and data assets	BOOST aims to demonstrate an open standardised and transformative shared data-driven Factory 4.0 model through 10 lighthouse factories
FAR-EDGE	723094	Decentrallized monitoring, control and analysis of production processes	FAR-EDGE aims to provide a reference implementation of emerging standards-based solutions for industrial automation (RAMI 4.0, Industrial Internet Consortium reference architecture)

The acronym's name is a link to the web page of the EU project solution.

Table 16. DIN Spec91345 RAMI 4.0 EU projects

2.1.8.4 Professional tools

Solutions*	Description
RAMI 4.0 Toolbox	Provides a framework for modelling an architecture based on cyber physical systems.

The solutions' name is a link to the web page of the company's solution developer.

Table 17. DIN Spec 91345 RAMI 4.0 Professional tools

2.2 Category - Vertical Integration

2.2.1 BatchML

2.2.1.1 Description

The Batch Markup Language (BatchML) is the XML implementation of the ISA-88 standard data structures, containing data structures for representation of batch, recipe and equipment information. Specifically, BatchML consists of a set of XML schemas (World Wide Web Consortium, 2016) written in the XML Schema Language (XSD) that implements the terminology and models in the ISA-88 standard. These schemas are used for two reasons: to create XML documents for exchanging batch data and to serve as the basis for corporate, system or application specific schemas that may be derived from the BatchML schemas[10].

[10] http://www.mesa.org/en/BatchML.asp

BatchML and B2MML schemas are based on the same definitions of common and core components, so that the two schema sets were merged into one unified ISA-95/88 schema group. A BatchML batch information structure is contained in OPC UA address space. OPC UA (OPC Unified Architecture) is a standard for communication in industrial applications developed by OPC Foundation around 2010. In the OPC UA address space, another batch list structure was used to represent the production records, since in BatchML the batch production records defined in the ISA-88 part 4, were not yet implemented (Virta et al., 2010).

BatchML was also found in (Lepuschitz et al., 2018), which is an ontology-based model for representing concepts of the batch process domain and it is used for the automated generation of an application in an industrial supervisory control and data acquisition (SCADA) system. The operations model of this ontology was mainly based on BatchML but was extended with additional information for supporting scheduling tasks.

2.2.1.2 State and maturity

There are 6 versions of BatchML. The initial version was released in 2010. The first version, V0100, was released in September 2012. The latest version is V0600, released in May of 2013. The V0600 contains the latest editions of the ISA-88 standard regarding Models and Terminology, Data Structures and Guidelines for Languages, General and Site Recipe Models and Representation and Batch Production Records.

2.2.1.3 EU projects

BatchML was not found in any EU project. However, since BatchML were integrated into B2MLL namespace, we refer the reader to subsection 2.3, that includes information about the latter.

Acronym*	GA	Solution	Description
No EU projects referencing BatchML have been found			

**The acronym's name is a link to the web page of the EU project solution.*

Table 18. BatchML EU projects

2.2.1.4 Professional tools

Solutions*	Description
BatchML-V0600-BatchProductionRecord.xsd	BatchML is an XML implementation of the ANSI/ISA-88, Batch Control, family of standards (ISA-88), known internationally as IEC 61512. BatchML consists of a set of XML schemas written using the World Wide Web Consortium's XML Schema language (XSD) that implements the models and terminology in the ISA-88 standard.

**The solutions' name is a link to the web page of the company's solution developer.*

Table 19. BatchML Professional tools

2.2.2 B2MML

2.2.2.1 Description

B2MML (Business to Manufacturing Markup Language) is part of the ANSI/ISA-95 (Galar et al., 2012) of standards, Enterprise-control System Integration (ISA-95). ISA-95 (International Society of Automation, 1945) provides a business application with independent information interfaces that connects business processes with Manufacturing Enterprise System (MES). B2MML is an open specification developed and maintained by the Manufacturing Enterprise Solutions Association (Muntean, M., Brândaş, C., & Cîrstea, n.d., 2019). B2MML V0700 (Awais et al., 2013)) was released in 2012. Previous versions are still available.

Specifically, BS2MML consists of a set of XML schemas written in the XML Schema Language (XSD) (Enge-Rosenblatt et al., 2011) to unify of the information that is exchanged between the MES systems and enterprise management systems(Thompson et al., 2009).

ISA-95 was developed in the 1990s and was adopted as IEC 62264 (Nannapaneni, S., Narayanan, A., Ak, R., Lechevalier, D., Sexton, T., Mahadevan, S., & Lee, n.d., 2019) international standard. It introduces a communication model based on 4 hierarchical levels that can be divided in two separated areas within a manufacturing company: the control domain (Level 3 and lower), where MES/MOM is implemented; and ERP systems (Level 4). B2MML is the data model used to connect applications between these two areas.

2.2.2.2 State and maturity

Any commercial company may adhere to the B2MML specification to integrate ERP or supply chain management systems and MES/MOM systems according to the ISA-95 standard. Some of the major companies like SAP or NAVISION include this standard.

2.2.2.3 EU projects

Acronym*	GA	Solution	Description
COSMOS	635405	Camelina & crambe Oil crops as Sources for Medium-chain Oils for Specialty oleochemicals	Final Report Summary from COSMOS describe use B2MML-based connector for MES/ERP.
PERFoRM	680435	Production harmonizEd Reconfiguration of Flexible Robots and Machinery	Periodic Reporting for period 2 from PERFoRM use B2MML a standard-compliant middleware.

**The acronym's name is a link to the web page of the EU project solution.*

Table 20. B2MML EU Projects

2.2.2.4 Professional tools

Solutions*	Description

B2MML Schemas	Contains the XSD Schema of B2MML

**The solutions' name is a link to the web page of the company's solution developer.*

Table 21. B2MML Professional tools

2.2.3 KPIs for Manufacturing Operations Management

2.2.3.1 Description

The standard Iso 22400 (International Standard ISO 22400-2, 2014), Automation System and integration - Key performance indicators (KPIs) for manufacturing operations management (Grossman, n.d., 2018), comes as a natural extension of the standard ISA-95 (Galar et al., 2012). Since the standard ISA-95 can be applied in the software industry, the information collected based Manufacturing Execution Systems/Manufacturing Operations Management (MES/MOM) system should be analysed and presented in a meaningful manner with the help of specific KPIs to the software industry.

This framework can provide date related for manufacturing system, in order to define KPIs for real-time industry evaluations. This framework will help structuring the KPIs and its measurement tools.

The ISO 22400 standard provides us with the terminology and methodology necessary to describe the KPIs, with the aim of managing manufacturing operations. To this end, this ISO has 34 KPIs that describe, by means of their formula, the elements necessary to evaluate the performance of manufacturing operations.

Effective business management operations should start with identification of key performance indicators (KPIs) that will help in decision making and will lead to improvement. It includes the prioritization of automation functions and the selection of relevant applications.

2.2.3.2 State and maturity

ISO 22400 is well established in the manufacturing industry. It has been implemented in other standards and data models. For instance, the section below describes KPIML. It is also promoted by the Autoware open-source association.

2.2.3.3 EU projects

Acronym*	GA	Solution	Description
There are no EU projects for Key Performance Indicators for Manufacturing Operations Management			

**The acronym's name is a link to the web page of the EU project solution.*

Table 22. KPIs for Manufacturing Operations EU Projects

2.2.3.4 Professional tools

Solutions*	Description
There are no professional tools for Key Performance Indicators for Manufacturing Operations Management	

*The solutions' name is a link to the web page of the company's solution developer.

Table 23. KPIs for Manufacturing Operations Professional tools

2.2.4 KPIML

2.2.4.1 Description

KPI-ML (Key Performance Indicator Markup Language) is an XML implementation of the ISO 22400 standard, Automation system integration – KPI performance indicators for manufacturing operations management (ISO 22400, 2014). KPIML consist of a set XML (eXtensible Markup Language) schema written in the XML Schema language (XSD) (Thompson et al. 2009).

The development of a generic set of KPIs that supports different kinds of manufacturing industries is challenging. To evaluate the performance of manufacturing operations, a total of 34 KPIs are presented in its ISO 2240. In this standard, the KPIs are described by means of their formula, corresponding elements, units of measure, timing and other characteristics. These KPIs are calculated at the MOM level within the industry. To do this we will need a response from the different systems from the production chain, which after processing them, we will send the final result to the business layer (Ferrer et al., 2018).

2.2.4.2 State and maturity

A first version of a Key Performance Indicator Markup Language (KPI-ML) has been defined in May 2015 by the Manufacturing Enterprise Solutions Association ((MESA, 1992).

2.2.4.3 EU projects

Acronym*	GA	Solution	Description
There are no EU projects for KPIML			

*The acronym's name is a link to the web page of the EU project solution.

Table 24. KPIML EU Projects

2.2.4.4 Professional tools

Solutions*	Description
KPI-ML V0100	Contains the XSD Schema of KPI-ML

*The solutions' name is a link to the web page of the company's solution developer.

Table 25. KPIML Professinal tools

2.2.5 ws-IBML

2.2.5.1 Description

ws-ISBM (Web Service Information Service Bus Model) is a SOAP Web Service implementation of the ISA 95.00.06 Messaging Service Model. The ws-ISBM defines a minimal interface subset to ESB (Enterprise Service Buses) and other message exchange middleware using a standard Web Service interface supported on top of channels and topics where through a consistent and unified model, ws-ISBM supports request-response and publish-subscribe message patterns.[11]

ws-ISBM is an open, supplier-neutral standard that can be used in any industry, as it allows the transmission of any information model, including MIMOSA CCOM, ISO 15926, MESA B2MML and OAGIS. The benefit from this approach is to allow applications to expose a single, standardized interface rather than having to be custom built for every version and format of ESB or message exchange system.

2.2.5.2 State and maturity

The OpenO&M ISBM specification was jointly developed by ISA and MIMOSA under the MIMOSA Technical Committee based on SOAP Web Services to provide a pathway to international standardization via IEC, as to allow different specifications' implementations using diverse technologies and design patterns.

ws-ISBM is currently available in version 2.0 from July 2020.

2.2.5.3 EU projects

Acronym*	GA	Solution	Description
ws-ISBM was not found in any relevant EU project.			

**The acronym's name is a link to the web page of the EU project solution.*

Table 26. ws-IBML EU Projects

2.2.5.4 Professional tools

Solutions*	Description
mimosa-org/ws-isbm	The latest stable version of ws-ISBM implementation
Assetricity SimpleISBM	fully implements the OpenO&M ws-ISBM and has been used and validated as part of the MIMOSA Oil and Gas Interoperability Pilot

**The solutions' name is a link to the web page of the company's solution developer.*

Table 27. ws-IBML Professional tools

[11] http://www.mesa.org/en/ws-ISBM.asp

2.2.6 OpenO&M

OpenO&M (Operation and Maintenance) is an initiative composed of multiple organizations, whose objective is to create open industry standards for the exchange of operation and maintenance data with business applications (Muntean, M., Brândaş, C., & Cîrstea, n.d., 2019). The initiative (or virtual organization) is maintained by MIMOSA, and composed of MIMOSA, ISA, MESA, OAGi, and the OPC Foundation, see **Figure 4**.

Figure 4. Organizations inside the OpenO&M initiative[12]

2.2.6.1 Description

The initiative's main objective is to enable more agile business operations and to provide the tools for condition-based maintenance and production operations. The initiative's standards cover multivendor interoperability al multiple levels within a manufacturing enterprise, from ERP (Enterprise Resource Planning) to process data collection.

As said in the beginning of the OpenO&M section, the initiative is maintained by MIMOSA. **MIMOSA** (Machinery Information Management Open System Alliance) is a non-profit organization that develops open information standards to enable collaborative asset lifecycle management and encourages the adoption of those open, supplier-neutral standards. These standards are manufacturing-related, support interoperability and key functional requirements for critical infrastructure management and enables Digital Twins definition for Big Data and analytics.

ISA (International Society of Automation) is a non-profit association whose objective is to create automation standards on demand. The association is formed of industrial automation engineers and technicians, that develop standards by helping members and other professionals solve their problems. ISA develops standards; certifies industry professionals; provides education and training; publishes books and technical articles; and hosts conferences and exhibits for automation professions.

MESA (Manufacturing Enterprise Solutions Association) International is a non-profit community of manufacturing companies, system integrators, information technology hardware and software suppliers, analysts, consulting service providers, and so on. The community's objective is to improve business results and production operations through optimized application of Information Technologies (IT). The association's efforts are focused on helping the manufacturing community to use IT to provide real-time visibility into the production process.

OAGi (Open Applications Group) is the owner and publisher of OAGIS (Open Applications Group Integration Specification), a canonical business language for information integration between all

[12] https://www.openoandm.org/

the components of an industrial company. This standard is defined to facilitate data exchange between enterprise applications to manufacturing and operation applications (vertical data exchange), between same level applications (horizontal data exchange), between verticals within one company and between different companies' verticals.

The **OPC Foundation** (Object linking and embedding for Process Control) is a non-profit organization dedicated to facilitating interoperability in automation by creating and maintaining open specifications for the communication of acquired process data, alarm and event records, historical data, and batch data to multi-vendor enterprise systems and between production devices.

2.2.6.2 State and maturity

The standard known as ISA-95 for automated communication between control and business systems, has been chosen by the main suppliers of MES systems (Manufacturing Execution System) and ERP (Enterprise Resource Planning) such as SAP. This model is used to exchange data between operation and maintenance activities at different levels.

Meanwhile, the specification set promoted by OpenO&M still have a relative implantation in the industry. The first initiatives have occurred in asset intensive industries such as Oil & Gas or wind power.

2.2.6.3 EU projects

Acronym*	GA	Solution	Description
OpenO&M was not found in any relevant project.			

**The acronym's name is a link to the web page of the EU project solution.*

Table 28. OpenO&M EU projects

2.2.6.4 Professional tools

Solutions*	Description
There have been initiatives such as OGI Pilot, but they are still far from being presented as professional tools.	

**The solutions' name is a link to the web page of the company's solution developer.*

Table 29. OpenO&M Professional tools

2.2.7 MIMOSA

2.2.7.1 Description

MIMOSA (Machinery Information Management Open System Alliance) promotes the use of open IT and IM standards for Critical Infrastructure Management on a cross-sector basis, addressing the highly heterogeneous and interdependent nature of critical infrastructure.

MIMOSA is defining and validating the Open Industrial Interoperability Ecosystem (OIIE) specification with OpenO&M initiative Members and Standards Leadership Council Members, including MESA/B2MML or ISA.

The OIIE is defined through an Industry Use Case Driven Methodology in concert with a standard overall IT and IM architecture, based fully on published, supplier-neutral standards and specifications. The OIIE Use Cases are developed to support prioritized industry functional requirements associated with the missions of MIMOSA, their members and their cooperation partners. They are specified based on the OIIE Standard Use Case Architecture, which spans from a basic story to the details needed for actual code implementation.

2.2.7.2 State and maturity

From the early 1993, MIMOSA has multiple collaboration partners from Standard Developer Organizations (SDO) to other industry associations where it continues to develop several activities to enable digitalization and interoperability for asset life-cycle management.

2.2.7.3 EU projects

Acronym*	GA	Solution	Description
SERENA	767561	plug-and-play cloud-based communication platform for managing the data and data processing remotely	Serena project aims to save time and money, minimizing the costly production downtimes
IMAIN	314304	Decision-making support software using service-oriented architecture based on standards such as MIMOSA aimed for establishment of optimal predictive and corrective maintenance strategy	IMAIN is a research project aiming to develop a novel decision support system for predictive maintenance. To that end, a multi-layer solution integrating embedded information devices and artificial intelligence techniques for knowledge extraction and novel reliability & maintainability practices was developed

**The acronym's name is a link to the web page of the EU project solution.*

Table 30. MIMOSA EU Projects

2.2.7.4 Professional tools

Solutions*	Description
MIMOSA was not found in professional tools	

**The solutions' name is a link to the web page of the company's solution developer.*

Table 31. MIMOSA Professional tools

2.2.8 Digital Twin for Manufacturing

2.2.8.1 Description

The ISO 23247 (Awais et al., 2013) series defines a framework to support the creation of Digital Twins(Enge-Rosenblatt et al., 2011) observables manufacturing elements including personnel, equipment, materials, manufacturing processes, facilities, environment, products, and supporting documents (Shao & Helu, 2020). A Digital Twin introduces us an identical and synchronized copy or representation of our system, both hardware and software levels.

ISO 23247-4 (International Standard ISO 23247-4, 2020) define four parts:

1. Overview and general principles (Requirements for developing Digital Twins in manufacturing).
2. Reference architecture with functional views.
3. Digital representation of manufacturing elements.
4. Information exchange between entities within the reference architecture.

Digital Twin aims to analyse the past to predict the future. Thanks to the live representation of the current system (managing all types of manufacturing including discrete and continuous manufacturing of assemblies and material). Digital Twins allows us to grow by collecting and analysing data.

The implementation of Digital Twins can be mainly found in the industrial sector, due to the fact that a lot of computer equipment is involved in the production lines or real-time data monitoring. All this data is processed with advanced Big Data techniques and this is where Digital Twins appears. Digital Twins allows you to process data and design a custom-made testing system. In addition, it is used to expose the system to real working conditions in order to evaluate how it behaves and make decisions.

A manufacturing Digital Twin offers an opportunity to optimize and simulate the production system (Nannapaneni, S., Narayanan, A., Ak, R., Lechevalier, D., Sexton, T., Mahadevan, S., & Lee, n.d., 2019). This including detailed visualization of manufacturing process from all components and logical aspects from production chain. The Digital Twin seeks to increase competitiveness, efficiency and productivity through encourage following main disciplines of production system. There are (Kritzinger et al., 2018):

- **Production planning and control**: Perform order planning based on statistics. This provides support in decision making.
- **Maintenance:** Identify the impact of changes and anticipate maintenance measures. It is necessary to collect the data relevant for the use case of interest rather than all available data from the physical system.
- **Layout planning**: Determinate how information should be provided form production system by the digital twin.

2.2.8.2 State and maturity

Digital twins are used to optimize machines or monitoring, diagnostic and prognostics. This standard can help enable manufactures making decision. It is currently under development at the committee draft stage. The goal is to provide a generic development framework for the use of digital twin in manufacturing(Grossman, n.d., 2018).

2.2.8.3 EU projects

Acronym	GA	Solution	Description
FASTEN	777096	Flexible and Autonomous Manufacturing Systems for Custom-Designed Products	Period 2 periodic reports speak of Digital Twin for manufacturing. They try to integrate a digital twin for manufacturing plants, providing a unified data model of the physical manufacturing line.

**The acronym's name is a link to the web page of the EU project solution.*

Table 32. Digital Twin for Manufacturing EU projects

2.2.8.4 Professional tools

Solutions*	Description
Framework under development	

**The solutions' name is a link to the web page of the company's solution developer.*

Table 33. Digital Twin for Manufacturing Professional tools

2.3 Category - OpenData

2.3.1 OData

2.3.1.1 Description

OData (Open Data Protocol) is an ISO/IEC approved OASIS standard (Huang, C. Y., Liang, S., & Xu, Y. (2013, n.d.) that defines a set of best practices for building and consuming RESTful APIs.

OData protocol enables the creation and consumption of REST APIs, which allow web clients to publish and edit resources, identified using URLs and defined in a data model, using simple HTTP messages, and shares some similarities with JDBC and ODBC, but OData is not limited to relational databases.

OData focus on business logic while building RESTful APIs without having to worry about the various approaches to define request and response headers, status codes, HTTP methods, URL conventions, media types, payload formats, query options, etc. OData also provides guidance for tracking changes, defining functions/actions for reusable procedures, and sending asynchronous/batch requests. The OData metadata, a machine-readable description of the data model of the APIs, enables the creation of powerful generic client proxies and tools.

2.3.1.2 State and maturity

The Microsoft company-initiated OData in 2007, and since then versions 1.0, 2.0, and 3.0 have been released under the Microsoft Open Specification Promise.

Version 4.0 was standardized at OASIS, with a release in March 2014. In April 2015 OASIS submitted OData v4 and OData JSON Format v4 to ISO/IEC JTC 1 for approval as an international standard.

2.3.1.3 EU projects

Acronym*	GA	Solution	Description
CryoLand	262925	GMES Service Snow and Land Ice	The CryoLand services on accurate and timely observations of snow and land ice by means of satellites are supporting many environmental and resource management activities in Europe.

**The acronym's name is a link to the web page of the EU project solution.*

Table 34. OData EU Projects

2.3.1.4 Professional tools

Solutions*	Description
Visual Studio Code for OData	It is a Visual Studio Code extension that adds rich support for the OData query language.
XOData	It is a generic online OData API/Service visualizer and explorer. It assists in rapid prototyping, verification, testing, and documentation of OData APIs. With XOData Chrome App it's also possible to explore OData Services deployed locally or on private networks.

**The solutions' name is a link to the web page of the company's solution developer.*

Table 35. OData Professional tools

2.3.2 OpenAPI

2.3.2.1 Description

The OpenAPI Specification (OAS) defines a standard, programming language-agnostic interface description for REST APIs, which allows both humans and computers to discover and understand the capabilities of a service without requiring access to source code, additional documentation, or inspection of network traffic. When properly defined via OpenAPI, a consumer can understand and interact with the remote service with a minimal amount of implementation logic. Similar to what interface descriptions have done for lower-level programming, the OpenAPI Specification removes guesswork in calling a service.

An OpenAPI definition can then be used by documentation generation tools to display the API, code generation tools to generate servers and clients in various programming languages, testing tools, and many other use cases.

2.3.2.2 State and maturity

The OpenAPI Specification is versioned using Semantic Versioning 2.0.0 (semver) and follows the semver specification.

For example, a valid OpenAPI 3.0.2 document, upon changing its openapi property to 3.1.0, *SHALL* be a valid OpenAPI 3.1.0 document, semantically equivalent to the original OpenAPI 3.0.2 document. New minor versions of the OpenAPI Specification *MUST* be written to ensure this form of backward compatibility.

An OpenAPI document compatible with OAS 3.*.* contains a required openapi field which designates the semantic version of the OAS that it uses. (OAS 2.0 documents contain a top-level version field named swagger and value "2.0".)

In July 2017, the OpenAPI Initiative released version 3.0.0 of its specification (Mainas, N., Petrakis, E. G., & Sotiriadis, S. (2017, n.d.). MuleSoft, the main contributor to the alternative RESTful API Modeling Language (RAML), joined the OAS and open-sourced their API Modeling Framework tool, which can generate OAS documents from RAML input.

2.3.2.3 EU projects

Acronym*	GA	Solution	Description
SPHINX	826183	A Universal Cyber Security Toolkit for Health-Care Industry	SPHINX aims to introduce a health tailored Universal Cyber Security Toolkit, thus enhancing the cyber protection of Health and care IT Ecosystem and ensuring the patient data privacy and integrity.
Lynx	780602	Building the Legal Knowledge Graph for Smart Compliance Services in Multilingual Europe	The Lynx project was conceived to mitigate the compliance problems faced by SMEs and companies when engaging in trade abroad, by connecting or interlinking legal and regulatory data from different jurisdictions and institutions at various levels (internationally, nationally, and regionally).
WEKIT	687669	Wearable Experience for Knowledge Intensive Training	Build on multi-discipline research (e.g., human-centred methodology integrates cognitive models, ergonomics, understanding of worker's well being) to accelerate how we identify, acquire and exploit skills valued by industry. Get high take-up by early adopters (e.g., in manufacturing).
TOPAs	676760	Tools for continuous building Performance Auditing	The TOPAs continuous performance auditing framework enables a better understanding of the actual energy performance in and across existing buildings and facilitates continuous performance improvement based on real operational use.

Acronym*	GA	Solution	Description
ZephyCloud-2	783913	Making Wind Energy More Profitable… Faster!	Assessing the future performance of a wind farm. The average duration of a wind farm is 20 to 25 years. Being able to predict the long-term profitability of a wind farm project is essential for the players involved in the exploitation of the wind resource. The technical issue of wind resource assessment (WRA) has a direct impact on the commercial value and on the ability to convince project funders (public and private).

**The acronym's name is a link to the web page of the EU project solution.*

Table 36. Open API EU projects

2.3.2.4 Professional tools

Solutions*	Description
Tools and Libraries	How it can create an OpenAPI definition, present it.
List of 3.0 implementations	Complete list of known tooling that implements the 3.0.0 specification.

**The solutions' name is a link to the web page of the company's solution developer.*

Table 37. Open API Professional tools

2.3.3 AsyncAPI

2.3.3.1 Description

AsyncAPI is an open-source initiative that seeks to improve the current state of Event-Driven Architectures (EDA). The long-term goal is to make working with EDAs as easy as it is to work with REST APIs. That goes from documentation to code generation, from discovery to event management. Most of the processes can be applied to REST APIs nowadays would be applicable to event-driven/asynchronous APIs too.

To make this happen, the first step has been to create a specification that allows developers, architects, and product managers to define the interfaces of an async API. Much like OpenAPI (fka Swagger) does for REST APIs.

2.3.3.2 State and maturity

The AsyncAPI specification (Muntean, M., Brândaş, C., & Cîrstea, n.d., 2019) settles the base for a greater and better tooling ecosystem for EDA's. Recently it has been launched AsyncAPI specification 2.0.0 —the strongest version to date— that will sustain the event-driven architectures of tomorrow.

2.3.3.3 EU projects

Acronym*	GA	Solution	Description
EU Projects NOT FOUND			

**The acronym's name is a link to the web page of the EU project solution.*

Table 38. Open API EU projects

2.3.3.4 Professional tools

On the AsyncAPI´s website there is a well-structured list of tools with their references.

Solutions*	Description
Code-first tools	Tools that generate AsyncAPI documents from your code.
Code Generators	Tools that generate code from an AsyncAPI document, and not the other way around.
Converters	Tools that do not yet belong to any specific category but are also useful for the community.
Documentation Generators	Tools that generate human-readable documentation from an AsyncAPI document.
DSL	Writing YAML by hand is no fun, and maybe you don't want a GUI, so use a Domain Specific Language to write AsyncAPI in your language of choice.
GitHub Actions	List of GitHub Actions that you can use in your workflows.
Mocking and Testing	Tools that take specification documents as input, then publish fake messages to broker destinations for simulation purpose. May also check that publisher messages are compliant with schemas.
Validators	Tools that validate AsyncAPI documents.

**The solutions' name is a link to the web page of the company's solution developer.*

Table 39. Open API Professional tools

2.3.4 OWL

2.3.4.1 Description

Web Ontology Language (OWL) is a family of languages used to describe the semantics in ontologies. OWL is defined by W3C Web Ontology Working Group published in 2004 based on a description logic called SHOIN(d) and it's defined in three variants: LITE, DL and Full. Later in 2009 OWL2 comes to review and extend its predecessor informally called OWL1 by being based in a SROIQ(d) where it introduces three OWL variants: EL, RL and QL were like the OWL1, being capable of more advanced reasoning than the former, respectively.

Like its predecessor, OWL 2 is designed to facilitate ontology development allowing data to be shared and reused across application, enterprise, and community boundaries. OWL family is based on RDF (Resource Description Framework) therefore, they share serializations and syntaxes which means that OWL ontologies can be stored as RDF documents.

In the same way a human makes a sentence, RDF uses a simple triple-based data model (Subject, Predicate and Object) to allow the representation of metadata using a graph-based formalism which is understandable by a machine characterizing a semantics layer. Each of the individual object or relationship between objects are identified with a unique identifier then can later be used to add more information to it. As stated previously, RDF has an XML serialization (RDF/XML) for ease of data exchange, and it has various textual representations for ease of human understanding.

On top of RDF, OWL consists of classes, properties (object or datatype), individuals (instances of classes) and restrictions where one of the main differences regarding OWL1 is related to the property axioms where the general inclusion can leverage the complexity of properties by joining simpler properties together. Thus, OWL2 data values which are stored as semantic web documents and can be represented using different syntax variants namely: Functional, RDF/XML, OWL/XML Manchester and turtle syntax.

Therefore, OWL enables richer integration and interoperability of data among descriptive concepts. OWL can be expressive when it comes to express very complex relationships about data. Since OWL are RDF triples the properties update or transformation can be flexible enough as it just needs to update the relevant triple. Thus, OWL allows to use data model to support many different kinds of reasoning tasks which can be used as well to minimize the data that are explicitly stored by minimising the queries interactions, as well as to retrieve that same reason.

2.3.4.2 State and maturity

Originally published in 2004, OWL has been revised and extended since then with more available features.

2.3.4.3 EU Projects

Acronym	GA	Solution	Description
DISASTER	285069	Semantic mediation	Disaster aims the data interoperability between different level of decision making to improve emergency responses

Table 40. OWL EU Projects

2.3.4.4 Professional tools

Solutions*	Description
StarDog	Semantic graph database
Protégé	Ontology editor and framework for building intelligent systems

**The solutions' name is a link to the web page of the company's solution developer.*

Table 41. OWL Professional tools

2.4 Category - Open Analytics and AI

2.4.1 Open Neural Network Exchange

Open Neural Network Exchange (ONNX) [13] is an open ecosystem that enables interoperability among AI models. It was created as a community project and it welcomes contributions from other developers. It is also available on github. ONNX is supported by partners such as Microsoft, Facebook and AWS. It can be used to provide flexibility in working with AI models, reduction of running time among others. Hardware companies like Nvidia and Intel produce hardware-optimized runtimes that can handle open format AI models like ONNX in order to keep up with this trend (Danopoulos et al., 2021).

2.4.1.1 Description

ONNX is an open source format that represents both deep learning and machine learning models. With ONNX, AI developers can more easily move between state-of-the-art tools and choose the combination that is best for them. ONNX supports many frameworks and operating systems. Its built-in optimizations can significantly speed up procedures like training. The ecosystem supports scripts from many programming languages, like Python, C++, Java and machine learning operations from Azure. Developers can use ONNX runtime feature to train a pytorch model or they can customize the feature. ONNX runtime can also be extended by adding custom operators and kernels.

ONNX can be found in recent literature, since it has been extensively used by researchers. In 2020, a parameterization has been proposed in (Wei-Fen Lin et al., 2019), particularly a compilation framework designed to connect ONNX (Open Neural Network Exchange) models to proprietary deep learning accelerators (DLAs). The proposed framework was ONNC (Open Neural Network Compiler).

2.4.1.2 State and maturity

ONXX was developed in 2017 and the latest version (v1.8) was announced in November 2020.

2.4.1.3 EU projects

Acronym*	GA	Solution	Description
ZDMP	825631	Zero Defect Manufacturing Platform	ZDMP project is combining state-of-the-art zero-defect technological approaches based on commercial-grade or open-source software, with built-in software for any gaps, and with an open development approach and app store.

[13] https://www.onnxruntime.ai/

**The acronym's name is a link to the web page of the EU project solution.*

Table 42. ONNX EU projects

2.4.1.4 Professional tools

The list of tools and frameworks that work with ONNX can be found in the website.

Solutions*	Description
Pytorch, LibSVM, Tensorflow, Matlab	ONNX can support well known frameworks to build a deep learning model.
NETRON, Visual DL	ONNX optimizer for fine tuning your model and visualization tools

**The solutions' name is a link to the web page of the company's solution developer.*

Table 43. ONNX Professional tools

2.4.2 Functional Mock-Up Interface

2.4.2.1 Description

The Functional Mock-up Interface (FMI) is a free standard that defines a standardized interface and container to develop complex cyber-physical systems for systems' computer modelling, simulation, validation and test.

The FMI standard was created during the European project MODELISAR, conducted by Dassault Systèmes, with the cooperation of a large number of software companies and research centres.

The FMI is based on the idea that a complex element can be defined by all the elements that form that complex element. Therefore, if a real product is to be assembled form a wide range of parts, each defined by a complex set of physical laws, then it should be possible to create a virtual product that can be assembled from a set of virtual models, each model representing the mentioned physical laws (Awais et al., 2013).

The FMI enables models exchange, co-simulation (Enge-Rosenblatt et al., 2011) and models' integration in Product Life-cycle Management, through the creation of FMI software libraries called FMU (Function Mock-up Unit).

2.4.2.2 State and maturity

FMI was the outcome of the project MODELISAR (2008-2011). Afterward, Modelica Association Project (MAP) took on FMI's management and development responsibility.

2.4.2.3 EU Projects

FMI is used in a significant amount of EU projects. Some examples of those projects are displayed in Table 44.

Acronym	GA	Solution	Description
INTO-CPS	644047	INtegrated TOol chain for model-based design of CPSs	The aim of the INTO-CPS project is to create an integrated tool chain for comprehensive model-based design of Cyber-Physical Systems (CPSs). The tool chain will support the multidisciplinary, collaborative modelling of CPSs from requirements, through design, down to realisation in hardware and software. This will enable traceability at all stages of the development.
CRESCENDO	234344	Collaborative & Robust Engineering using Simulation Capability Enabling Next Design Optimisation	The IMG4 project CRESCENDO addresses the Vision 2020 objectives for the aeronautical industry by contributing significantly to the fulfilment of three specific targets of the aeronautical industry's Strategic Research Agenda. CRESCENDO will develop the foundations for the Behavioural Digital Aircraft (BDA), taking experience and results from VIVACE, and integrating these into a federative system and building the BDA on top of them.
ASTERICS	314157	Ageing and efficiency Simulation & TEsting under Real world conditions for Innovative electric vehicle Components and Systems	The concept of the ASTERICS project comprises a systematic and comprehensive approach for the design, development and testing phases of E-drivelines in Pure Electric Vehicles, which is based upon four major building blocks: (1) real world environment and conditions based drive cycles, (2) advanced testing methodologies and models for E-driveline components, (3) descriptive/ predictive models for battery subsystem, power electronics and electric motor and (4) total system (e-driveline and EV).
ECO-SEE	609234	Eco-innovative, Safe and Energy Efficient wall panels and materials for a healthier indoor environment	The ECO-SEE solution to the problem of IEQ in energy efficient buildings has been to develop novel building products with the capacity to improve the quality of the indoor environment using their intrinsic chemical and physical qualities, as well as through improved design modelling to enable more effective utilisation of these products for the betterment of indoor environmental quality.
ITESLA	283012	Innovative Tools for Electrical System Security within Large Areas	The iTesla project has developed a toolbox able to support the operation of the pan-European electricity transmission system in the coming years and has validated the different functionalities of this toolbox with datasets of various complexity and size.

Table 44. Functional Mock-Up Interface EU Projects

2.4.2.4 Professional tools

It is supported by more than 150 tools and maintained as a Modelica Association Project on GitHub. Some professional tools' examples are displayed in **Table 45**.

Solutions*	Description
CATIA	Computer-Aided Three-Dimensional Interactive Application.
IGNITE	A tool to model complex physical systems and their sub-systems. IGNITE is a physics-based package developed for complete vehicle system modelling and simulation.
OpenModelica	OPENMODELICA is an open-source Modelica-based modeling and simulation environment intended for industrial and academic usage.
PyFMI	PyFMI is a package for loading and interacting with Functional Mock-Up Units (FMUs).
Simulink	Simulink is a MATLAB-based graphical programming environment for modeling, simulating and analyzing multidomain dynamical systems.
Sulca	SULCA software allows the user to perform Ecodesign and various kinds of Life Cycle Assessments (LCA).
Volta	The collaborative web platform for Simulation Process and Data Management and design optimization.

**The solutions' name is a link to the web page of the company's solution developer.*

Table 45. Functional Mock-Up Interface Professional tools

2.4.3 PMML - Predictive Model Markup Language

2.4.3.1 Description

PMML has becoming the leading standard for statistical and data mining models and is supported by over 30 vendors and organizations. With PMML, it is easy to develop a model on one system using one application and deploy the model on another system using another application, simply by transmitting an XML configuration file (Nannapaneni, S., Narayanan, A., Ak, R., Lechevalier, D., Sexton, T., Mahadevan, S., & Lee, n.d., 2019). Since PMML is an XML-based standard, the specification comes in the form of an XML schema.

PMML provides a way for analytic applications to describe and exchange predictive models produced by data mining and machine learning algorithms, and also supports common models such as logistic regression and other feed forward neural networks.

PMML is developed by Data Mining Group (DMG) an independent, vendor led consortium that develops data mining standards. The Data Mining Group is a consortium managed by the Center for Computational Science Research, Inc., a non-profit founded in 2008. The Data Mining Group also developed a standard called Portable Format for Analytics, or PFA, which is complementary to PMML.

A PMML file can be described by the following components:

- Header: contains general information about the PMML document, such as copyright information for the model, its description, and information about the application used to generate the model such as name and version. It also contains an attribute for a timestamp which can be used to specify the date of model creation.
- Data Dictionary: contains definitions for all the possible fields used by the model. It is here that a field is defined as continuous, categorical, or ordinal (attribute optype). Depending on this definition, the appropriate value ranges are then defined as well as the data type (such as, string or double).
- Data Transformations: transformations allow for the mapping of user data into a more desirable form to be used by the mining model. PMML defines several kinds of simple data transformations such as, Normalization, Discretization, Value mapping, Functions and Aggregation.
- Model: contains the definition of the data mining model. E.g., A multi-layered feedforward neural network is represented in PMML by a "NeuralNetwork" element which contains attributes such as, Model Name (attribute modelName), Function Name (attribute functionName), Algorithm Name (attribute algorithmName), Activation Function (attribute activationFunction), Number of Layers (attribute numberOfLayers).

2.4.3.2 State and maturity

First version 0.7 was released on July 1997 and PMML 4.3 was released on August 23, 2016, and new features include: new Model Types (Gaussian Process and Bayesian Network), New built-in functions, Usage clarifications, Documentation improvements.

2.4.3.3 EU projects

Acronym*	GA	Solution	Description
SOL-EU-NET	IST-1999-11495	Data Mining and decision support for business competitiveness: Solomon European Virtual Enterprise	The goal of this project is to enhance competitiveness and find new business opportunities in the global IT market by establishing a virtual European enterprise composed of companies and research laboratories with highly specialised expertise in two IT areas: data mining and decision support.

**The acronym's name is a link to the web page of the EU project solution.*

Table 46. PMML EU Projects

2.4.3.4 Professional tools

Solutions*	Description
-	There are several companies, a long list, that have specific solutions that support specific Model Types.

*The solutions' name is a link to the web page of the company's solution developer.

Table 47. PMML Professional tools

2.4.4 PFA - Portable Format for Analytics

2.4.4.1 Description

PFA is an emerging standard for statistical models and data transformation engines. PFA combines the ease of portability across systems with algorithmic flexibility: models, pre-processing, and post-processing are all functions that can be arbitrarily composed, chained, or built into complex workflows. PFA statistical models and data transformation engines are described as a JSON or YAML configuration file. PFA is complementary to PMML (Grossman, n.d., 2018).

PFA encapsulates a unit of data processing called a scoring engine that provides a common interface to safely deploy analytic workflows across environments, from embedded systems to distributed data centers.

PFA-enabled analysis tools produce their results as JSON documents with a structure defined by the PFA specification. If a machine learning algorithm produces a classifier that we wish to apply to a large cluster-bound dataset. If it produces that classifier in PFA format, a PFA-enabled host running on the cluster can execute it in a safe, controlled way.

PFA is similar to the Predictive Model Markup Language (PMML), an XML-based specification for statistical models, but whereas PMML's focus is on statistical models in the abstract, PFA's focus is on the scoring procedure itself.

2.4.4.2 State and maturity

PFA is a new open standard model interchange format supported and developed by Data Mining Group (DMG) an independent, vendor led consortium that develops data mining standards. Actual version is v0.8.1.

2.4.4.3 EU projects

Acronym*	GA	Solution	Description
EU Projects NOT FOUND			

*The acronym's name is a link to the web page of the EU project solution.

Table 48. PFA EU Projects

2.4.4.4 Professional tools

Developer tools that speak PFA can deploy their scoring engines (e.g., classifiers, predictors, smoothers, filters) on production environments that understand PFA. The only connection between the two worlds is the PFA document, a human-readable text file. In fact, this text file could have contributions from several statistical packages, or it could be modified by JSON-manipulating tools or by hand before it is delivered.

Solutions*	Description
-	-

**The solutions' name is a link to the web page of the company's solution developer.*

Table 49. PFA Professional tools

3. Alignment

FUNCTION (✗ or ✔)

STANDARD		Control							Operations					Information						Application		Bussiness	
		Sensing	Actuation	Communication	Entity Abstraction	Modelling (edge analytics)	Asset management	Execution	Provisioning and Deployment	Asset Management	Monitoring and Diagnostics	Prognostics	Optimization	Data Ingestion	Quality of data	Syntactical transformation	Semantic transformation	Data persistence and storage	Data distribution	Logic and rules	APIs and UIs	Business	I4Q vertical
Open Automation	Field Device Integration	✔	✔	✔	✔	✗	✔	✗	✗	✔	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✔
	OPC UA	✔	✔	✔	✔	✗	✗	✗	✗	✔	✔	✗	✗	✔	✗	✔	✗	✗	✗	✔	✗	✗	✔
	MTConnect	✔	✔	✔	✔	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗	✗	✗	✔	✗	✗	✗	✗
	PLCopen	✔	✔	✔	✔	✗	✗	✔	✗	✗	✗	✗	✗	✔	✗	✗	✗	✗	✗	✔	✗	✗	✔
	COLLADA	✗	✗	✗	✔	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗	✗	✔	✔	✗	✗	✗	✔
	CAEX	✗	✗	✗	✔	✔	✔	✔	✔	✗	✗	✗	✗	✔	✗	✗	✗	✔	✔	✗	✗	✗	✗
	AutomationML	✔	✔	✔	✔	✔	✔	✔	✔	✗	✗	✗	✗	✔	✗	✗	✗	✔	✔	✗	✗	✗	✔
	DIN Spec 91345 RAMI 4.0 (AAS)	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✗	✗	✔	✗	✗	✗	✔	✔	✔	✔	✗	✔

Vertical Integration	BatchML	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✓	✓	✗	✓	✗
	B2MML	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✓	✓	✗	✓	✗
	KPIs for Manufacturing Operations Management	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
	KPIML	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗
	ws-IBML	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✓
	OpenO&M	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
	MIMOSA	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
	Digital Twin	✓	✓	✓	✓	✓	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✓	✓	✗	✓	✓
Open Data	OData	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓
	Open API	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓
	AsyncAPI	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓
	OWL	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓
Open Analytics and AI	ONNX	✗	✓	✗	✗	✓	✗	✓	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗	✓	✓	✗	✓	✓
	Functional Mock-Up Interface	✗	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓
	PMML	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
	PFA	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓

The alignment shows that the identified models and ontologies cover most of the functional domains defined in IIRA: However, Syntactical and Semantic transformation and i4Q verticals are the functions for which there seems to be less models and ontologies covered for the benchmarking. This is definitively an important aspect to consider in the recommendations and interoperability guidelines extracted from this analysis.

If we focus on the different categories, there is clearly an alignment between the different categories and the main functional domains. Open Automation covers mostly control functions, since these models are mainly designed for representing manufacturing equipment. The standards of the vertical integration category cover more functions at the operational level since these functions are aimed at implementing centralised management and control functions across distributed industrial control systems. Open Data is primarily addressed to the information domain, as these standard models facilitate the exchange of information between systems, and the final user. Apart from that, they provide APIs and UIs to expose the data. The last category is Open analytics and AI, these standards cover more control and operational functions as these models support the modeling and distribution of analytical functionalities.

On the other hand, RAMI 4.0 AAS and Digital twin are the most comprehensive models, covering a wide range of functionalities in the IIRA model. This is mainly because these models target specifically Industrial IoT applications and integrate different complementary models and standards into a unified framework. RAMI 4.0 incorporates other prominent standards, mainly OPC UA and AutomationML, and AutomationML in turn incorporates aspects of different specifications (COLLADA, CAEX, PLCOpen). Together with these specifications, the RAMI 4.0 AAS covers most of the functional domains in IIRA. OpenO&M is another standard that aggregates different models and that consequently covers a wide range of functionalities, mainly under the Operations functional domain.

4. Benchmarking

4.1 Open Automation

Table 50 contains the results of the benchmarking of the different models and ontologies defined for the different models under the Open Automation category.

Open Automation	Coverage	Maturity/reach	Ease of use	Integration and Deployment complexity
Field Device Integration	++	+++	+++	++
OPC UA	+++	+++	+++	++
MTConnect	++	+++	-	+
PLCOpen	++	+++	+++	++
COLLADA	+++	+++	+++	++
CAEX	+++	-	+++	+++
AutomationML	+++	+++	+++	+++
DIN Spec 91345 RAMI 4.0 (AAS)	+++	++	+++	+++

Table 50. Benchmarking – Open Automation

The different solutions under analysis do not cover to the same extent all the pilots. OPC UA seems like a good candidate in all use cases, and it is specifically mentioned as a solution enabler in Pilot 2: Diagnostics and IoT Services. CAEX is mainly used for plant modelling and it is not quite applicable in the use cases of machine tool providers that deal with machine components (i.e., Pilot 1: Smart Quality in CNC Machining) or machines (e.g Pilot 2). COLLADA is primarily used for 3D modelling which a priori does not seem aligned with the solution proposal drafted at the time for writing for Pilot 1. On the other hand, the Pilot 5: Advanced In-line Inspection for incoming Prime Matter Control might not require the modelling of the PLC control provided by PLCOpen, as the current draft description points towards an integration at the MES/MOM level.

Regarding the maturity/reach, most of the analysed solutions have a good level of maturity and reach. OPC UA is the standard that has a greater level of penetration in the European manufacturing industry and is becoming a de-facto standard for the exchange of information with the floor plant level. The same applies to FDI, which, as described above, has a good support from industry. MTConnect has also a good level of penetration and there are tools and development resources available. AutomationML and related specifications, mainly PLCOpen and COLLADA have also a good level of maturity and reach. However, partners have not identified many solutions or development resources for CAEX. Although it is a recent specification, partners have also identified a rapid adoption of RAMI 4.0 and AAS, although it has not yet reached the same level of maturity as the other models and standards analysed.

As for ease of use, both MTConnect and OPC UA are well documented communication standards, which apply known best practices in TCP/IP industrial communications. OPC UA is very versatile, and provides different options (e.g., Pub/Sub or Server / Client patterns) to adapt to different use case scenarios, and in that sense, it requires more know-how and expertise to fine tune its configuration to a specific use case, but still, it is relatively easy to use. The same considerations apply to FDI. PLCOpen, COLLADA, CAEX, and in extension AutomationML are based on XML, which is a well-known format for data exchange. Finally, the RAMI 4.0 AAS, together with companion specifications, provides an additional layer of abstraction on top of OPC UA and AutomationML and in that sense, it exhibits a similar usage complexity.

Regarding integration complexity, the main objective of FDI is to facilitate the integration of new field devices and in that sense, the integration and deployment complexity is low. OPC UA and MTConnect require IP connectivity and in that sense, there are alternatives that might be easier to integrate and deploy particularly at lower levels in the floor-plant hierarchy, although this is in part mitigated for OPC UA, through FDI. Again, the use of XML makes it relatively easy to integrate AutomationML and related specifications, and in extension, RAMI 4.0 has a similar deployment complexity as the components it is based on.

In summary, the benchmarking from Open automation shows that the identified models and ontologies are generally easy to use.

4.2 Vertical Integration

Table 52 contains the results of the benchmarking of the different models and ontologies defined under the Vertical Integration category.

Vertical Integration	Coverage	Maturity/reach	Ease of use	Integration and Deployment complexity
BatchML	+	---	-	+
B2MML	+++	+++	+++	+
Key Performance Indicators for Manufacturing Operations Management	+++	+++	+++	+
KPIML	+++	---	+++	+
ws-IBML	+	-	+++	+++
OpenO&M	+	--	+++	++
MIMOSA	+++	+++	+++	+++
Digital Twin	+++	---	++	+

Table 51. Benchmarking – Vertical Integration

OpenO&M and related standards (BatchML, B2MML, ws-IBML) target the integration between different organisational levels, specifically between the operational level (e.g., primarily MES/MOM and WMS) and business planning and logistics (e.g., ERP, PLM, BI). Therefore, these models are better aligned with the solutions for production companies (i.e., pilots 3 to 6) than with the solutions for machine tool providers (i.e., pilots 1 and 2). MIMOSA provides a comprehensive model of common entities and events found in any use case. The same can be applied to the digital twin for manufacturing, which covers all the hierarchical levels of production systems.

Having said that, regarding the level of maturity and reach of B2MML, this model is meant to be a common data definition to link business level with management systems derived from ISA-95, which has become a de-facto industry standard to model the exchange of information between the business level and the operations level. There are many ontologies and models that have followed the same communication model, such as KPIML. Although it is a very mature specification, other related models have not yet reached the same level of maturity, for instance BatchML or KPIML. On the other hand, Digital twin is a rather recent standardisation effort by ISO and consequently it does not have a high level of maturity or reach at the time of writing. However, it is worth noting that it provides with a framework for obtaining and controlling information, and also gives a vision of the entire system architecture of its different functional views, which is important in vertical integration.

All these models are easy to use. In general, they are logical structures in XML, which is a well-known format for data exchange, that must be implemented between the business layer and the logic layer. On the other hand, Key performance indicators for ML or MOM, define KPIs for real-time industry evaluations and are easy to implement. MIMOSA or OpenO&M facilitates access to information on manufacturing environments. However, although they are easy to use this models or ontologies, they are somewhat difficult to integrate, since they require previous knowledge to be implemented.

4.3 Open Data

Table 54 contains the results of the benchmarking of the different models and ontologies defined under the Open Data category.

Open Data	Coverage	Maturity/reach	Ease of use	Integration and Deployment complexity
OData	+++	+++	+++	+++
Open API	++	+++	+++	+++
AsyncAPI	+++	+++	+++	+++
OWL	+++	---	++	+

Table 52. Benchmarking – Open Data

OData and OpenAPI provide models to define and implement synchronous REST APIs using the HTTP protocol. These interfaces are not very well suited for field communications (i.e., interfase in pilots 1 and 2), due to timing constraints, but rather, for the definition of interfaces between applications at higher levels (primarily business applications). AsyncAPI provides models to define and implement asynchronous APIs using a similar approach, but for asynchronous communications using for instance the Publish / Subscribe pattern. AsyncAPI is protocol agnostic and can be used to model communications in any event-driven application. OWL can be used to integrate different models and create a rich ontology to support all use cases, and it can definitively be applied in all use cases.

Regarding maturity and reach, OpenAPI is very mature and has a very large development community. OData is also rather mature and is backed by big industry players like SAP and Microsoft. On the other hand, AsyncAPI is a rather recent initiative, although it is rapidly gaining momentum. Moreover, OWL is a rather well stablished standard format to support the definition and persistence of ontologies. In summary, all the models and standards in this category support a simpler interaction between system components, and between solutions, and exhibit a relatively high maturity level.

As for the ease of use, integration and deployment complexity, ODATA, Open API, and AsyncAPI provide a YAML model to support the definition of the application interfaces. This makes it very easy to use by both humans and machines. OWL uses XML, and therefore it is also rather easy to use and to deploy, although it requires some expert knowledge to seize the full potential of the specification.

4.4 Open Analytics and AI

Table 55 contains the results of the benchmarking of the different models and ontologies defined under the Open Data category.

Open Analytics and AI	Coverage	Maturity/reach	Ease of use	Integration and Deployment complexity
Open Neural Network Exchange	+++	+++	++	++
Functional Mock-Up Interface	+	+++	+++	+++
PMML	+++	+	+++	+++
PFA	+++	+	+	+

Table 53. Benchmarking – Open Analytics and AI

AI and analytics are rather ubiquitous across pilots and in that sense, all the models seem in general adequate to cover pilot use cases. ONNX, PMMI are specific for machine learning models, PFA is specific for analytic functions, and FMI for dynamic simulation models, however, at the time of writing it is not possible to specify what models may be more relevant in each particular use case.

Despite that all the models and specifications are rather recent, they all are backed by a strong development community, in that sense, they all exhibit a good level of maturity, although ONNX and FMI have a higher maturity and reach.

Regarding ease of use, ONNX is supported off-the-shelf in many machine learning development frameworks and therefore it is very easy to use. Likewise, FMI has a strong support, and it is very well documented and relatively easy to use. Although there are open-source resources for PMMI and PFA, they still do not have the level of support of ONNX or FMI.

From and integration and deployment viewpoint, the integration and deployment of the different models imposes specific requirements in the runtime and in the deployment workflows to support this specific persistence models, but in general there are deployment patterns and runtime environment to support these formats.

5. Interoperability Guidelines

In the context of the i4Q project, interoperability refers to the capability of the different components to connect, communicate, and operate together via the Internet of Things. This includes the humans, the smart factories, and the relevant technologies. This poses a significant challenge particularly in the manufacturing domain, where production processes process does not simply follow a predetermined set of methods or steps and involve only the people, machines, and processes that are directly involved. Interoperability requires an entire environment with fluid interaction and flexible collaboration between all the components. For example, assembly stations are not separate from the products created or the people who are working on them.

The following sections contain a set of guidelines to foster interoperability across i4Q solutions, based on the use of and alignment to the models described and analysed in previous sections.

5.1 Open Automation

From the benchmarking results shown above, the integration of i4Q solutions with manufacturing equipment, mainly components and machines, should support to the best extent possible the RAMI 4.0 AAS specifications. The administration shell uses the OPC UA protocol as the core communication standard for operational data, and AutomationML models for the exchange of design and engineering information. The benchmarking shows that both types of models are relevant in the pilots and have a good level of maturity and reach, so the alignment to these specifications is very beneficial for i4Q solutions. The RAMI 4.0 AAS already provides a package file format to enable the exchange of information, and in this sense, the administration shell provides comprehensive specifications to model and exchange engineering and operational data. Together, this framework provides support to different i4Q solutions as shown in Table 57.

Additionally, OPC UA partner specifications like OPC UA over TSN enable some the key technologies envisioned in edge communications. Regarding the pilots, there are a set of companion specifications that provide data and communication models for specific sectors. For instance, the EUROMAP 77 specification provides additional specifications on top of OPC UA to model and integrate injection moulding machines, which is relevant in Pilot 6: Automatic Advanced Inspection of Automotive Plastic Parts. In this companion specification, OPC UA provides the fundamental data models and communication mechanisms to exchange sensor data and actuation commands with devices, while the companion EUROMAP 77 specifies detailed data models for specific injection moulding devices and detailed communication protocol specifications to enable features like Plug&Play. It is therefore recommended to use additional models or companion specifications as a reference to better define the interface of solutions with manufacturing equipment. Next section provides further information on this topic.

Solution	Models	Comments
i4Q Digital Twin	AutomationML, AAS	AutomationML and the AAS provide an abstraction level to model manufacturing equipment
i4Q Data Integration Services	OPC UA, OPC UA companion specs, AAS	OPC UA provides a protocol stack to connect the digital twin with its physical counterpart. Companion specs provide specific models for verticals (e.g. plastic injection)
i4Q IIoT Security Handler	OPC UA	Provides security mechanisms to protect data in transfer
i4Q Trusted Networks with Wireless & Wired Industrial Interfaces	OPC UA, OPC UA companion specs	Real time communications support via TSN. Furthermore, together with FDI the solution can be extended to enhance the support for field communications.
i4Q Rapid Quality Diagnosis	AutomationML, CAEX, COLLADA	Provide standard 3D modeling formats to represent manufacturing equipment

Table 54. Open Automation Guidelines

5.2 Vertical Integration

The previous section described how models like OPC UA and AutomationML can be beneficial to foster the interoperability between i4Q solutions and manufacturing equipment. The alignment to standards in the vertical integration category can be beneficial primarily in two ways.

First, these standards introduce additional information about the operational context of the manufacturing equipment, their organization in the floor plant, the processes, and the relationship with other resources, like materials, or human resources, including KPI definitions and calculations. All this additional context information allows algorithms to perform better data analytics, better reasoning and better inference.

Secondly, these standards facilitate the integration of i4Q solutions with systems in higher levels, ranging from MES/MoM systems to ERP systems, in order to automate quality assurance and improve the support to quality management operations, based on objective KPIs. The analysis showed that the MIMOSA ecosystem and companion standards like KPIML provide rich models to contextualize manufacturing equipment data.

Additionally, the standard interfaces defined by OpenO&M and related standardization bodies provide standard methods to integrate i4Q solutions into operation and maintenance management workflows. The recommendation is to align the models and ontologies of i4Q solutions to these specifications to:

Solution	Models	Comments
i4Q Services for Data Analytics	Key Performance Indicators for Manufacturing	Provides precise definitions and methods to calculate manufacturing KPIs which can be relevant in many data analysis functions
i4Q Data-driven continuous process qualification		
i4Q Manufacturing Line Reconfiguration Toolkit		
i4Q Prescriptive Analysis Tools		
i4Q Big Data Analytics Suite	KPIML, OpenO&M	Provides standard interfaces to integrate data workflows with higher level systems
i4Q Data Integration and Transformation Services		

Table 55. Vertical Integration Guidelines

5.3 Open Data

Open data specifications facilitate the specification and implementation of the interfaces between i4Q components as well as between i4Q components and external systems. Open API development resources include libraries and code generators to automate the generation of clients, servers, or gateway components from the service specification, so it is very convenient to use this industry standard for the definition of REST APIs. The OData to OpenAPI mapping allows Open API tools to be used with OData services and applications. Some outstanding examples of the latter are MS Excel, MS Power BI, MS Navision, or SAP Gateway.

Moreover, AsyncAPI provides models to define asynchronous interfaces and facilitate the integration of i4Q solutions in event driven architectures. This architecture allows simplifies horizontal scalability in distributed computing models and make this more resilient to failures.

Finally, OWL provides a rich framework to define an ontology for i4Q solutions, integrating the different models into a common representation of the different entities and the relationships between them.

Solution	Models	Comments
i4Q Blockchain Traceability of Data	OData and OpenAPI	OData and OpenAPI can be used to define and provision REST backend services to manage blockchains and simplify the integration and interoperability with other systems

Solution	Models	Comments
i4Q Data Integration and Transformation Services	OData and OpenAPI	OData provides standard Interfaces to access data, including options and functions to filter or aggregate data
i4Q IIoT Security Handler	Open API	Can be used to define the specifications of REST APIs and facilitate the integration with other systems
i4Q AI Models Distribution to the Edge		
i4Q Edge Workloads Placement and Deployment		
i4Q Digital Twin Simulation Services		
i4Q Manufacturing Line Reconfiguration Toolkit		
i4Q Big Data Analytics Suite	AsyncAPI	Can be used to define the specification of asynchronous data interfaces to define data workloads with higher level systems
i4Q Edge Workloads Placement and Deployment		

Table 56. Open Data Guidelines

5.4 Open Analytics and AI

The analysis of the different models and formats for authoring, persisting, and sharing analytic models, including machine learning and simulation models. These models and open formats facilitate the integration, deployment and distribution of the analytic parts of i4QSolutions. Analytical components can use a single implementation of common functions to load a model in one of these formats into the runtime, and to connect to the rest of the i4Q Solutions, and therefore the use of ONNX and FMI can be beneficial for:

Solution	Models	Comments
i4Q AI models distribution to the edge	PMML, ONNX, FMI	Provide distributable file formats for different types of analytical components such as predictors, simulators or optimizers
i4Q Data-driven continuous process qualification	PMML, ONNX	Provide standard formats to model, distribute and Interface with AI models.
i4Q Manufacturing Line Reconfiguration Toolkit	ONNX	Provide standard formats to model, distribute and Interface with AI models.

Solution	Models	Comments
i4Q Prescriptive Analysis Tools	FMI	Provide standard formats to model, distribute and interface with simulation models
I4Q Digital Twin	FMI ONNx	Provide standard formats to model and distibute data driven (ONNx) or pyhsical system dynamics simulation models (FMI)

Table 57. Open Analytics and AI Guidelines

6. Liaison with on-going activities

There are different on-going projects and standardization activities that i4Q should be liaised with. This section lists some of the on-going activities which i4Q should liaise with to foster interoperability.

6.1 OntoCommons Project

The main objective of the OntoCommons project is to advance on the standardisation of data formats for the distribution of manufacturing and materials science data in order to ensure interoperability. OntoCommons coordinates different activities to coordinate relevant stakeholders for the development of a common ontology and model ecosystem according to concrete standardisation rules. The liaison with this initiative yields a suitable approach to harmonise the definition of data models and ontologies for i4Q, while at the same time making them findable to a wide user community, interoperable with other technologies, and reusable in other initiatives.

6.2 FoF ZDM Cluster

The Zero Defects Cluster (ZDM) is a European initiative within the Factories of the Future (FoF) Zero Defects Manufacturing priority, which aims to lay the foundations of a new holistic approach for quality assurance in industry. Within this cluster, there are several ongoing standardisation activities which are relevant for the i4Q project. At this stage, all initiatives are conformed as working groups in the European Committee for Standardization (CEN), or CEN Workshop Agreements (i.e a working group with a signed agreement developed and approved in the context of CEN). Their names and proposed scopes are:

- Zero Defects Manufacturing Terminology CWA: This working group aims to define a standard terminology for zero defects manufacturing. The objective is to provide a standard definition that update the classical concept of zero defects manufacturing taking into account recent technological advancements (i.e., Industry 4.0 and Industry 5.0). These new definitions are linked to prominent standards in areas like metrology, or quality management and it is therefore relevant for i4Q Solutions. The alignment with this initiative provides a precise definition and positioning of the scope of the different i4Q solutions in zero defects manufacturing.
- Digital Manufacturing Platforms (DMP) Data Exchange: The main objective of this working group is to define standard interfaces for data exchange in digital manufacturing platforms. The data workflows regarded are data exchange between platforms and devices (e.g., how to connect to manufacturing equipment), or data exchange between platforms (e.g. how to consume data of a device connected to a different platform in an i4Q solution).

6.3 AI4EU Project

The Artificial Intelligence for the European Union (AI4EU) Project aims is a strategic research project on Artificial Intelligence. The main objective is to advance on the creation of a solid AI ecosystem in the European Union. The platform will provide a platform that gathers knowledge, algorithms, and development resources to facilitate the development and integration of AI based solutions. AI4EU is based on the open source Acumos AI platform for the development, instantiation and deployment of trained AI models. Thus, the AI4EU Platform contains a large catalogue of AI solutions and a liaison with this initiative will make i4Q solutions more visible to the entire EU AI community.

7. Action Plan

Finally, the section below contains a detailed action plan targeting specific tasks in the i4Q project plan, based on the general interoperability guidelines and liaison with on-going activities described above.

Action	Task	Priority	References
Use the ISA-95 conceptual standard for manufacturing operations (resource management, planning, scheduling, control, recipe management) to Identify key users of i4Q Solutions in manufacturing operations and maintenance. This will ensure that the architectural definitions are aligned with the standard frameworks for vertical integration	Business Viewpoint	High	ISA-95
Regard developers of analytical components (AI learning models, algorithms, data analytics) as key stakeholders of i4Q Solutions. These models will be integral parts of industrial control systems and it is important to capture the fundamental capabilities that their providers expect from the i4Q system	Business Viewpoint	High	None
Align the usage viewpoint definitions (activities, roles, tasks, etc) to the ISA-95 conceptual standard for manufacturing operations. This will facilitate the mapping of the functional and implementation features of i4Q solutions to the standard frameworks for vertical integration	Usage Viewpoint	Medium	ISA-95
Define a model for the life-cycle management of analytical components which is aligned with ISA 95, ISA-62443 and RAMI 4.0 as part of the usage viewpoint definitions. This will ensure that the functional and implementation components required to support analytical components in its entire life-cycle are taken into consideration.	Usage Viewpoint	Medium	ISA-95 ISA-62443 RAMI 4.0
Define common i4Q models and ontologies to ensure the semantic interoperability of i4Q analytical components. Use MIMOSA	Functional Viewpoint	High	MIMOSA RAMI 4.0 AAS

Action	Task	Priority	References
and the RAMI 4.0 AAS definition as a scaffold and extend with i4Q specific needs			
Identify operational and maintenance data workflows and interfaces between i4Q solutions and manufacturing assets, either manufacturing equipment (sensors, actuators, controllers) or software systems (ERP, MES/MOM, BI), based on the conceptual standards used as a reference for the usage viewpoint. This will provide a clear picture of the interfaces between i4Q solutions and external devices and systems in a standard framework	Functional Viewpoint	High	ISA-95 RAMI 4.0 OpenO&M Open API OData AsyncAPI
Identify data workflows and interfaces for the distribution of i4Q analytical solutions and considering the different phases in their life-cycle, from development to de-commissioning	Functional Viewpoint	Medium	RAMI 4.0 ONNX FMI PMML PFA Open API
Define a system architecture for technical components which is consistent with the rest of the architectural viewpoints and in extension with the identified models and standards	Implementation Viewpoint	High	RAMI 4.0 ISA-95 ISA-62443
Define the technical specifications of the interfaces for the exchange of operational and maintenance data between i4Q solutions and manufacturing assets, based on the RAMI 4.0 AAS and OpenO&M models and related standards	Implementation Viewpoint	Medium	RAMI 4.0 OPC UA AutomationML OpenO&MB2MMLOData
Define the technical specifications of the interfaces for the distribution of analytical components integrated in industrial control systems, based on the analysed models and formats, and taking into account the specifications for the distribution in other platforms, particularly AI4EU	Implementation Viewpoint	Medium	ONNX FMI PMML PFA

Action	Task	Priority	References
Collect specific technical requirements of the devices and software systems that i4Q Solutions must connect to in the different pilots	Requirements Analysis and Functional Specification	High	RAMI 4.0 OPC UA AutomationML OpenO&MB2MMLOData
Define a liaison agreement to publish i4Q analytical solutions in the AI4EU project with the objective of promoting the software deliverables and at the same time ensure interoperability with other solutions in the European AI ecosystem	Impact Activities: Awareness and Outreach, Community Building	High	ONNX FMI PMML PFA
Identify i4Q project partners participating in on-going CEN CWAs to ensure the representation of the interests and objectives of the projects in these working groups	Standardisation	Low	N/A

Table 58. Action Plan

References

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