Selection of a Data Exchange Format for Industry 4.0 Manufacturing Systems

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***Abstract*—With the emergence of the Industry 4.0 concept, or the fourth industrial revolution, the industry is bearing witness to the appearance of more and more complex systems, often requiring the integration of various new heterogeneous, modular and intelligent elements with pre-existing legacy devices. This challenge of interoperability is one of the main concerns taken into account when designing such systems-of-systems, commonly requiring the use of standard interfaces to ensure this seamless integration. To aid in tackling this challenge, a common format for data exchange should be adopted. Thus, a study to select the foundations for the development of such a format is hereby presented, taking into account the specific needs of four different use cases representing varied key European industry sectors.**

I. Introduction

Technological developments have always been the cornerstone of what is normally referred to as an "Industrial Revolution", be it the mechanization, electrification or digitalization of production [1]. These disruptions consist essentially in large paradigms shifts originating from the need to fulfil both varied and varying market requirements.

Coincidentally, over the last few years there has been an increase in the demand for highly customised products, making a clear change from a seller's to a buyer's market. This trend of increasingly up-to-date, individualised products (i.e. batch size one) translates into a need for manufacturers to become more and more agile in order to deal with these rapid market changes, as well as flexible [2], particularly in production, due to the sheer amount of variants and variables. These factors are once again fuelling such a revolution, albeit a planned one, which is being referred to as "Industry 4.0". This vision revolves around six core design principles [3], namely advocating decentralization, virtualization, real-time capability, service orientation, modularity and of particular interest for the topic of data representation and harmonization, the principle of interoperability.

This movement has spiked the interest of researchers worldwide and in particular in Europe, given its German origins, which has resulted in the emergence of several European funded projects focused on this topic. Such is the case of the H2020 Production harmonized Reconfiguration of Flexible Robots and Machinery (PERFoRM), which will be introduced in I-A and to which this technology assessment pertains. Afterwards, Subsection I-B contextualizes the importance of standard interfaces and common semantics as key enablers of interoperability within project itself.

A. The PERFoRM Project

The PERFoRM project is aligned with the Industry 4.0 vision aiming the conceptual transformation of existing industrial production systems towards plug and produce production systems to achieve flexible manufacturing environments based on rapid and seamless reconfiguration of machinery and robots as response to operational or business events. An important assumption, as an innovation action, is not to create a new system architecture from scratch but instead to use the best results of successful previous R&D projects, like SOCRADES [4], IMC-AESOP [5], GRACE [6], IDEAS [7] and PRIME [8]. This consideration will help the industry adoption of these new and emergent solutions.

The PERFoRM achievements will be validated in four different industrial use cases covering different industrial automation systems, ranging from home appliances to aerospace and from green mobility to large compressor production. This diversity of use cases introduces different requirements in terms of data models, touching, amongst others, maintenance, logistics, sensorial data, Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) data.

B. Standard Interfaces for Interoperability

An important key issue to ensure the interoperability in real industrial environments, interconnecting heterogeneous legacy hardware devices, e.g., robots and Programmable Logic Controllers (PLCs), and software applications, e.g., Supervisory Control and Data Acquisition (SCADA), MES and databases, is to adopt standard interfaces. These aim to define the interface between devices and applications in a unique, standard and transparent manner, ensuring the transparent pluggability of these heterogeneous devices. For this purpose, a standard data representation should be adopted by the interface that should also define the list of services provided by it, and the semantics data model handled by each service. In this definition, and particularly for industrial automation, several ISA 95 layers addressing different data scope and requirements should be considered, namely the machinery level covering mainly L1 (automation control) and L2 (supervisory control) layers, and

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the backbone level covering the L3 (manufacturing operations management) and L4 (business planning and logistics) layers. The achievement of the complete interoperability and pluggability requires to complement the use of standard interfaces with adapters to transform the legacy data representation into the native standard interface data representation.

The remainder of this paper is organised as follows: Section II introduces some of the main standards (and their implementations) for data representation and modelling, along with their coverage of relevant concepts which act as differentiation criteria. Subsequently, Section III describes the methodology to be used for the selection of the aforementioned technologies, detailing each step of the decision process. Consequently, Section IV entails the application of this methodology for the technology assessment, along with a brief discussion of the results. Finally, Section V proposes a few underlining conclusions, followed by some acknowledgements.

II. Technologies for Data Representation and Modelling

One of the main challenges presented for Industry 4.0 is the representation and seamless exchange of data originating from heterogeneous elements, often from very different, albeit related, action levels. A clear example using the ANSI/ISA-95 standard [9] terminology would be the harmonization of data pertaining to the Enterprise Resource Planning (ERP), to the Manufacturing Execution System's (MES) layer and to Supervisory Control And Data Acquisition (SCADA) systems.

Coincidentally, the subject of standardization is consistently indicated by the industry as one of the major obstacles for the industrial acceptance of disruptive technologies [10]. In fact, several European funded projects have already made some efforts to push towards this goal. Some examples include the BatMAS [11] and FP7 PRIME [12] projects. The latter highlights the importance of a common semantic language and data representation in order for proper interoperability and pluggability to be achieved, due to the plethora of heterogeneous entities involved in these intelligent, complex manufacturing systems [13].

In fact, over the last few years several industrial standards have emerged, each providing a set of semantic definitions for data modelling and exchange across different areas of the manufacturing industry. An example is the IEC 62264 standard [14], which is based on the aforementioned ANSI/ISA-95. IEC 62264 entails a framework aimed at facilitating the interoperability and integration of both enterprise and control systems.

Other existing standards include IEC 61512 [15], based on ANSI/ISA-88 and focusing the batch process domain, ISO 15926 [16] aimed at process plants, IEC 62424 [17] for the exchange of data between process control and P&ID tools and IEC 62714 [18], centred on industrial automation systems engineering data.

A. Standard Implementations and Selected Technologies

As a direct consequence of this emergence, some mostly XML-based implementations of the specifications defined in these standards have been developed. The list presented below has been selected from the pool of technologies currently available and documented in the literature which stand out as potentially fulfilling some or most of PERFoRM's semantic needs.

- **IEC 61512 BatchML** (T_1) - An XML implementation of the ANSI/ISA-88 Batch Control family of standards. It offers a variety of XML schemas written in XML Schema Language (XSD) that implement the ISA-88 specifications.
- **IEC 62264 B2MML** (T_2) - Implements the ANSI/ISA-95 family of standards for Enterprise-Control system integration via XML schemas written in XSD. The latest versions of BatchML's schemas were integrated into the B2MML namespace, now using the B2MML common and extension files. Despite this fact, for the purpose of this study both implementations will still be considered separately.
- **ISO 15926 XMplant** (T_3) - Provides access to process plant information in a neutral form, following the ISO 15926 specifications, supporting structure, attributes and geometry of schematics and 3D models;
- **IEC 62424 CAEX** (T_4) - Computer Aided Engineering Exchange (CAEX) [19] is an object-oriented, neutral, XML-based data format that allows the description of object information, such as the hierarchical structure of a plant or series of components. Its scope spans across a wide variety of static object types, such as plant, document and product topologies as well as petri nets;
- **IEC 62714 AutomationML** (T_5) - AutomationML is an XML-based data format that builds upon other well established, open standards spanning several engineering areas, aiming at interconnecting them. More specifically, CAEX serves as the basis of hierarchical plant structures, while COLLADA and PLCopen XML are the foundations for geometry/kinematics and control applications, respectively [20];
- **OPC UA's Data Model** (T_6) - OPC UA defines a very generic object Data Model (DM) supporting relationships between objects (references) and multiple inheritance. It is used by OPC UA to represent different types of device data, including metadata and semantics;
- **MTConnect** (T_7) - MTConnect is a manufacturing standard [21] presenting an XML-based format for data exchange between the shop-floor and software applications for monitoring and analysis. This includes device data, identity, topology and design characteristics such as axis length, speeds and thresholds. It also possesses a set of specifications to ensure interoperability with OPA UA;

B. Selection Criteria

During the literature review process, the following criteria were selected with the specific goals of the PERFoRM project in mind. As such, each of them relates to a given specific area of focus targeted in the project. In order for them to be used for the assessment in section IV, a general description of each one is presented below.

- **Process domain specific concepts** (C_1) - Covers the aspects associated to specific methods of production, including for instance batch, flow and job production;
- **Performance analysis** (C_2)- Entails information that enables the assessment of production performance, including start time, end time, location or status such as the percentage of completion;
- **Quality monitoring** (C_3) - Concepts enabling the monitoring of production quality, ensuring that products consistently meet the expected quality requirements. As an example, this can include reject and scrap tracking structures, inspection data, and quality tests;
- **Material resource management** (C_4) - Relates to the existence of specifications for material classes, material lots or sublots and even QA (Quality Assurance) tests that may be exchanged between business systems and manufacturing operations systems;
- **Production planning and scheduling** (C_5) - This criterion relates to the capacity to describe information to be exchanged and used by for instance (using ISA-95 terminology) ERP systems and MES, detailing production goals and schedules to achieve said production targets;
- **Recipe management** (C_6) - Inclusion for instance of master recipes, recipe formulas or recipe ingredients;
- **Product description** (C_7) - This relates to the capacity to describe information associated to a product, such as production rules, assembly instructions, bill of materials and bill of resources;
- **Maintenance** (C_8) - Maintenance descriptions should detail information regarding maintenance operations, such as requests, responses and work orders. Relevant associated information should also be present, which can include dates, times, personnel involved, descriptions, status and technical information, among others;
- **Failure and alarm management** (C_9) - Deals with information structures that enable the handling and management of failures and alarms, such as categories, definitions, priorities, timestamps and hierarchies;
- **Engineering life-cycle data** (C_{10}) - Information pertaining specifically to the engineering life-cycle domain, namely system design or simulation (e.g. CAD models);
- **Supply-chain data** (C_{11}) - This criterion encompasses information related to the supply chain. A few examples include shipment data, orders, distributor information and transactions.
- **Extendibility** (C_{12}) - Possibility to extend and add further information *a-posteriori*;
- **Process control** (C_{13}) - This relates to process control at the PLC-Level, including pertinent data such as signals, I/O and control sequences;

C. Technology Summary

Through an analysis of current literature, as well as of each technologies' own documentation, it is possible to relate each of them to the aforementioned criteria. The result from this process is summarized in Table I. Blank spaces indicate that either a given criterion is not covered, or that no reference to it was found in neither the respective technology's documentation nor in the literature. Criteria marked with an "*X*" are fully addressed, while those marked with "*-/X*" are either partially or not directly covered.

TABLE I
ANALYSED STANDARDS AND THE ASSOCIATED DIFFERENTIATION CRITERIA (ADAPTED FROM [11])

	T_1	T_2	T_3	T_4	T_5	T_6	T_7
C_1	X		X	X	X		
C_2		X					
C_3		X					
C_4		X					
C_5		X					
C_6	X						
C_7		X		-/X	-/X		
C_8		X	X		-/X		-/X
C_9		X				-/X	-/X
C_{10}			X		X		
C_{11}		-/X					
C_{12}	X	X		X	X	X	X
C_{13}	-/X				X	X	X

A clear conclusion that can be drawn from the analysis of Table I is the fact that no single standard covers the entire spectrum of relevant criteria to match PERFoRM's needs. As a consequence, a possible solution could be derived from the combination of two or more of these technologies, hence the need for a proper selection methodology to be developed.

III. Decision Making Methodology

The selection of the adequate technology to perform a specific task is, most of the time, a complex and subjective process. Its complexity is mostly related with the product's characteristics, and how they correlate to the consumer's wishes. For each customer, the product's number of features and their importance are the key analysed elements. Hence, for a technology assessment, this is not a simple process either. There are several factors that must be analysed and should be taken in consideration for every step of the decision process. Therefore, the decision process is defined by the following five steps.

Step 1: Criteria definition and description.
The first step of the presented methodology is the criteria definition and description, necessary to evaluate each technology. Each criteria, C_i, where $i \in \mathbb{N}$, must be provided by the literature review and should represent the end users's wishes. Each criteria evaluated by only two values, "0" or "1", which are translated into the existence or non-existence of each specific feature.

Step 2: Relevance definition.
In this second step, the objective is to define the level of

importance of each criteria for the end user. This factor is defined by W_i, where $i \in \mathbb{N}$. For each criteria the weight must be defined by a scale, from 1 to 10. In this step the end users are asked to, through a questionnaire, provide the importance of each criteria to be present in the final product.

After the definition of these two decision factors, criteria and relevance, it is necessary to evaluate the technology.

Step 3: Technology assessment.
The third is the technology assessment process, defined by(T_{Score_k}) , where $k \in \mathbb{N}$. In this process the two evaluation factors are combined to create a score. Each technology is evaluated in accordance with the importance, W_i, that each end user gives to each criteria C_i. To proceed to the technology evaluation, eq. 1 is applied.

$$T_{Score_k} = \frac{C_1W_1 + ... + C_nW_n}{W} = \frac{1}{W}\sum_{i=1}^{n} C_iW_i \quad (1)$$

Where W is determined by eq. 2.

$$W = \sum_{i=1}^{n} max(W_i) \quad (2)$$

And, where $n \in \mathbb{N}$. The results from the use of eq. 1 correspond to the evaluation of one technology by one end user. So, in order to have a global validation of the technologies, by all end users, it is necessary to aggregate each of their opinions.

Step 4: Data aggregation process.
The goal of the fourth is to define a methodology to aggregate the end users opinions regarding each technology. To do so, two new factors are determined. Firstly, the average ($\overline{X}_{T_{score_k}}$), which is defined by eq. 3.

$$\overline{X}_{T_{score_k}} = \frac{\sum_{k=1}^{n} T_{score_k}}{n} \quad (3)$$

Where $n \in \mathbb{N}$. This factor (average) determines the point in which the opinions are centred. Secondly, the standard deviation ($S_{T_{score_k}}$), which is defined by eq. 4.

$$S_{T_{score_k}} = \sqrt{S^2_{T_{score_k}}} = \sqrt{\frac{\sum_{k=1}^{n}(T_{score_k} - \overline{X}_{T_{score_k}})^2}{n-1}} \quad (4)$$

Where $n \in \mathbb{N}$. The standard deviation defines the level of agreement, by the end users, in the evaluation process.

Step 5: Ranking of the assessed technologies.
The final step is to rank the technologies based on the combined opinions from the end users. So, in order to combine them, a fuzzy inference system (FIS) is suggested. The FIS combines both presented factors, $\overline{X}_{T_{score_k}}$ and $S_{T_{score_k}}$, in order to define a score for each technology (Fig. 1).

Based on this score, all the technologies are ranked. The technology(ies) which presents the higher score(s) is(are) considered the most adequate for the purpose of the PERFoRM project.

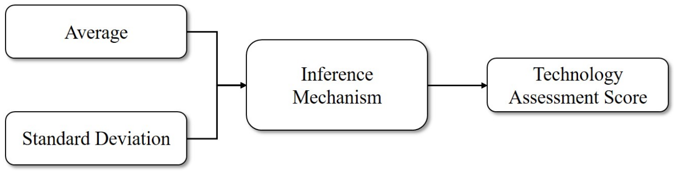

Fig. 1. Consensus-based model (Adapted from [22])

IV. Technology Assessment

A. Presumptions

During the development of this work, some presumptions were assumed in order to apply the designed methodology.

1) All the criteria marked with ”-/X” will be considered as non-existent, since they cannot fulfil the required purpose in its entirety;
2) The model considers that all criteria are self-contained.

B. Evaluation Procedure

For the technology assessment, the methodology was applied as follows.

Step 1: Criteria definition and description.
During the development of the present study all the criteria were defined in accordance with the literature review, and with the features defined in section II. each of the 13 defined features is relevant for the technology assessment developed under the scope of PERFoRM project.

Step 2: Relevance definition.
To determine the relevance of each criteria for the end users (spanning across different industrial areas), each was asked to answer a small questionnaire. This questionnaire aimed to establish, from ”1” to ”10”, the importance of each criteria in the decision process. The end users are defined as E_m, where $m \in \{1, 2, 3, 4\}$. The evaluation of each end user is presented in Table II.

TABLE II
Importance of the criteria for the end users

	E_1	E_2	E_3	E_4		E_1	E_2	E_3	E_4
W_1	7	10	7	3	W_8	9	10	2	10
W_2	9	10	10	8	W_9	10	7	3	10
W_3	8	10	8	10	W_{10}	3	10	5	10
W_4	6	10	3	5	W_{11}	3	10	7	10
W_5	10	10	1	8	W_{12}	8	10	2	10
W_6	3	10	2	5	W_{13}	6	10	2	10
W_7	6	10	4	3					

After the collection of the presented data, step 3 could then be applied.

Step 3: Technology assessment.
In this step the technology was evaluated based on the application of eq. 1. Table III summarizes the opinions of the respective end user for the evaluation of each technology.
Based on this information, it is necessary to aggregate the data.

TABLE III
TECHNOLOGY ASSESSMENT (PER END USER)

	E_1	E_2	E_3	E_4		E_1	E_2	E_3	E_4
T_1	0.14	0.23	0.08	0.14	T_5	0.18	0.31	0.12	0.25
T_2	0.51	0.59	0.25	0.49	T_6	0.11	0.15	0.03	0.15
T_3	0.15	0.23	0.11	0.18	T_7	0.11	0.15	0.03	0.15
T_4	0.12	0.15	0.07	0.10					

Step 4: Data aggregation process.
For the data aggregation, eq. 3 and eq. 4 were be applied. The results are presented in Table IV.

TABLE IV
DATA AGGREGATION

	$\overline{X}_{T_{score_k}}$	$S_{T_{score_k}}$		$\overline{X}_{T_{score_k}}$	$S_{T_{score_k}}$
T_1	0.15	0.06	T_5	0.22	0.08
T_2	0.46	0.15	T_6	0.11	0.06
T_3	0.17	0.05	T_7	0.11	0.06
T_4	0.11	0.05			

Step 5: Raking of the assessed technologies.
The last step is to apply the consensus based model, although it is necessary to validate said model through three tests. The first of which being the extreme conditions test (Fig. 2).

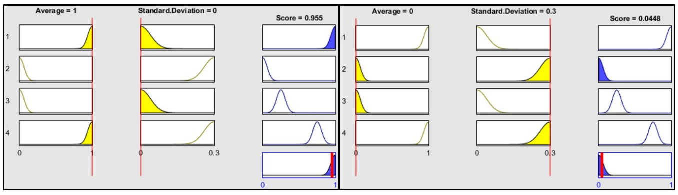

Fig. 2. Extreme conditions' test

In this test, the model is forced into the most extreme conditions analyse the results coeherence. The tests are in accordance with the expected valus, near to maximum and minimum, respectively. So, if the average is high and the standard deviation is low, the score is high, and on the contrary, if the average is low and the standard deviation is high, is it expected for the score's result to be low, as can be seen in Fig. 2. The following test is the face validity test (Fig. 3).

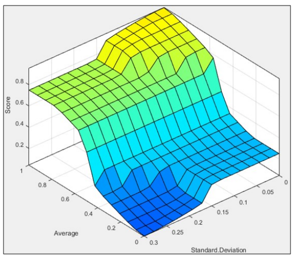

Fig. 3. Face validity test

In this test some irregularities can be analysed and corrected, if they exist. If any irregularity is spotted the model should be corrected in order to present an upward/downward trend. As can be seen in Fig. 3, the surface presents an upward tendency, which indicates a well defined model. The final test is the behavioural test (Fig. 4).

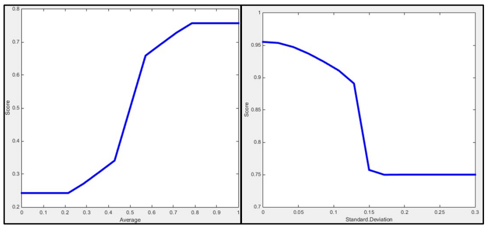

Fig. 4. Behavioural test

This test, along with the face validity test, indicates the behaviour of the model, and based on it, it is possible to stablish its adequacy. For this specific case, it is possible to identify the upward trend, from the average perspective, and the downward tendency, for the standard deviation point of view.

Thus, once the model is validated, it can be used to analyse the data from Table IV. The results and the ranking are presented in Table V.

TABLE V
SCORE GENERATED BY THE CONSENSUS-BASED MODEL AND TECHNOLOGIES RANKING

Ranking Position	Technology	Score (%)
1	B2MML (T_2)	35.7318
2	AutomationML (T_5)	25.0641
3	XMplant (T_3)	25.0051
4	BatchML (T_1)	25.0026
5	OPC UA DM (T_6)	25.0009
6	MTConnect (T_7)	25.0009
7	CAEX (T_4)	25.0008

According to the ranking table (Table V), the most adequate technology for the PERFoRM project is B2MML, followed by AutomationML.

C. Discussion of Results

Analysing the results from the Table V, there are several aspects that may raise some doubts. The values that are presented to rank the technologies present two distinct characteristics:

1) The values are very close to each other;
2) None of their scores is placed over the 50th percentile, out of 100%.

These two aspects are fully correlated and based on the fact that the developed methodology is set on three distinct aspects:

- The users interests;
- The importance that each user gives to the evaluated characteristics;
- The number of end users.

The end users' interests are mostly related to the areas in which their own (often very different) production lines' challenges emerge. Taking this into account, the established criteria weights vary in accordance with each vision. This weight variance, which can be seen in Table II, added to the low number of end users may translate into some instability in the technology assessment (Table IV).

Being this discrepancy so high, technologies which match a high number of criteria (in this case T_2), can be influenced severely (Table IV) by this lack of consensus. This fact is translated in the score (Table V) by a higher percentage, although, it is still under the 50% mark.

For the other technologies, the low number of characteristics linked to higher weights (Table I and Table II) gives them, based on an uniform average value and a low discordance, close and relatively high score values.

V. Conclusion

Within the scope of the PERFoRM project, several different standards for data modelling and representation were studied, along with their respective implementations, in order to identify the best foundation to achieve the project's interoperability goals.

To this end, a selection methodology was developed in order to assess and match each technology against specific differentiation criteria, defined in accordance with the project's requirements. The application of said methodology resulted in the ranking presented in Table V, with B2MML appearing as the frontrunner. However, as previously stated in Section II, from the analysis of Table I it is clear that no single technology covers the entire spectrum of requirements defined for the project, hence justifying a possible combination of different technologies/standards.

Moreover, through a closer look at Table I, it can be said that a joint solution using B2MML and AutomationML (particularly for the lower-level data, which is lacking in the former) would cover most of the criteria presented. This is specially true if we take into account the criteria which are marked as only partially covered, despite them being disregarded in the methodology application.

This is further supported by the results obtained from this study, presenting B2MML and AutomationML as the two highest rated technologies in regards to the relevance of their coverage to the project's use cases' interests.

As a result, future work will consist in the development of a common language format for seamless data exchange based on these two technologies, which will act as the main driver of interoperability within the PERFoRM project.

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