IoT-Based Automatic Non-conformity Detection: A Metalworking SME Use Case

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Abstract Industrial production's main goal is to achieve adaptability, resource efficiency, as well as, to integrate the complete value and supply chains, including customers, in business and value processes. To this end, manufacturing systems need to be as generic as possible in order to answer the different needs of a variety of industries. Industry4.0 paradigm stands as the baseline to answer these requirements, and data collection capabilities represent a major pillar in this strategy. Moreover, the way companies interact and communicate, being able of sharing information among themselves as well as to take full advantage of the data and knowledge being generated (even within the same company) demand huge attention to solving interoperability issues. The C2NET project (Cloud Collaborative Manufacturing Networks project), intends to implement the Industry 4.0 vision aiming to provide a cloud-based platform for managing the company interactions and promoting enterprise interoperability. This paper presents how the Data Collection Framework (DCF) developed within C2NET project can be used to collect data and support an automatic non-conformity detection case in a Portuguese metalworking SME. The developed components are briefly described as well as the implemented use case. The results obtained are also presented and discussed.

Keywords Enterprise interoperability · Data collection · Resource virtualization

1 Introduction

"Industry 4.0" has become the new paradigm in what regards the reality of industrial production in the years to come. The main goal of Industry 4.0 is to realize the

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so-called intelligent factory whose main characteristics are adaptability and resource efficiency together with the possibility of integrating the complete value and supply chains, including customers, in business and value processes. To achieve this objective, industrial companies need to be capable of handling more complex and stricter requirements in a variety of fields (e.g., data collection, flexibility) while ensuring to maintain, or increase, the requested production capacity. Nowadays, companies are encouraged to think globally while acting and staying locally economically compatible. Similarly, inside the factory, enterprise level strategy must concerted with local actions at lower level (e.g., device level). In addition to this, the industrial manufacturing systems of this 4th industrial revolution intend to reposition several components, (e.g., Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) layers), so that these can be deployed in a web-based or cloud-based environment, in order to enable its adaptation to the concept of collaborative networks [1]. In this context, manufacturing systems need to be as generic as possible in order to answer the different needs of a variety of industries. Industry 4.0 paradigm stands as the baseline to answer these requirements, and data collection capabilities represent a major pillar in this strategy to enable real-time information on production system operation. The data collection needs to include not only the collection of data from shop floor devices or resources but also the manipulation of the enterprises information systems that handle orders and schedules. Thus, interoperability demands are extremely high. The C2NET project (Cloud Collaborative Manufacturing Networks project) intends to implement the Industry 4.0 vision aiming to provide a cloud-based platform for managing the company interactions and promoting enterprise interoperability. According to the architecture of C2NET project [2], the Data Collection Framework (DCF) consists of a dedicated layer designed for collecting and managing the data of the industrial networks resources. This data includes Internet of Things (IoT) data from the shop floor (e.g., sensors) and legacy systems data resources (e.g., ERP). This way, data definition appears linked to a set of resources that are managed via middleware systems, i.e., hubs. Regarding this research work, this paper presents the steps performed to solve interoperability challenges regarding collection and use of scattered and heterogeneous data in a specific context of a use case from a Portuguese metalworking SME. The collected data is used to detect the occurrence of abnormal situations that can lead to delays in production orders and affect the overall performance of the company. Next sections are organized as follows: Sect. 2 presents a brief state of the art on related areas, Sect. 3 provides an overview of developed Data Collection Framework (DCF), Sect. 4 describes the interoperability needs identified and how they can be tackled through the implemented use case, and Sect. 5 provides specific insight into results obtained for validating the approach. In Sect. 6, some conclusions are drawn and future work lines are presented.

2 State of the Art

2.1 Enterprise Interoperability

Enterprises are constantly seeking for solutions capable of optimizing their assets aiming to increase their business benefits and reinforce their competitiveness. The available ICT and connectivity solutions are attracting companies that intend to globally spread their operations, in investing in interoperability solutions. The so-called *inter-enterprise interoperability*, besides creating an easy communication channel with clients, enables the networking between different enterprises supported by ICT-based technologies. Moreover, similar processes are being applied within the same company (*intra-enterprise interoperability*) in order to facilitate the use of information being generated on different departments, systems and devices, and eliminating issues related with duplicate information, information formats, etc. This degree of interoperability is the focus of this paper in which the collection and use of scattered and heterogeneous data is explored. One of the major problems of this interaction is the heterogeneity of data coming from different sources [3]. When focusing on the technical aspects of interoperability, two levels can be defined: A low-level interoperability in which connection and communication are established and a high-level interoperability in which the objective is to enable system interaction and understanding.

Regarding the low level, systems use well-defined formats for exchanging messages and, in IoT environments, technologies for Wireless Sensor Networks (WSN) and Machine-to-Machine (M2M) are the most prominent. WSN can be implemented using different protocols (e.g., Bluetooth (IEEE 802.15.1), Near Field Communication (NFC), Radio-Frequency Identification (RFID), IEEE 802.15.4 wireless personal area network (WPAN), WIFI (IEEE 802.11), 3G/4G and ETHERNET (IEEE 802.3)) and the selection of the most appropriate one must take into consideration aspects such as desired speed and working environment [4]. Regarding M2M, several initiatives have been recently developed, from which the ETSI M2M Service Architecture [5] is an example. In addition, MQTT (Message Queuing Telemetry Transport—http://mqtt.org/) is a lightweight messaging protocol especially used when remote connections are required and bandwidth is not an issue.

Regarding the high-level interoperability, the main challenge is to find a common ground for the involved systems. To this end, ontologies and other model-based technologies have been extensively used as they provide a shared understanding of a specific domain. In Semantic Web's, "an ontology" is defined as a set of classes in a domain area that shows the properties and the relations between those classes [6]. To establish an ontology on a specific domain, we have to select an ontology language (OWL or RDS/RDFS) and an ontology engineering approach (bottom-up: starting from the specific concepts and, by generalization, builds a structure; top-down: starting from the generic concept and, by specialization, builds a structure; middle-out: identifying central concepts in each domain). Ontology development can be supported by ontology development life-cycle tools (from creation to maintenance and evolution). Some examples include: Protégé [7, 8] and the Topic Maps 4 E-Learning—TM4L [9]. Current developments in this area, integrating both low-level and high-level interoperability strategies, include cloud-based platforms that support enterprise interoperability (such as C2NET platform [10]). These solutions tend to be plug and play platforms that, although requiring some configuration work, enable the access to a set of new and improved services.

2.2 Enterprise Resources Virtualization

Smart enterprise is a term coined by entrepreneur and investor Joe Lonsdale, describing a new breed of computing companies focusing on "enabling knowledge workers to process and analyze massive amounts of heterogeneous data and to collaborate and monitor things." On a high level, this encompasses killing waste/inefficiencies, redesigning collaboration and surfacing untapped data in new potent ways for big, monolithic industries that exist today [11]. In addition to this vision, the term ubiquitous computing (proposed by Mark Weiser) [12] envisages a smart environment in which sensors, actuators, interfaces and other elements are seamlessly embedded into common objects which are connected with each other via a network. The transference of this vision to manufacturing (smart) environment [13] leads to the next development step, which addresses the fusion of both physical and digital/virtual world [14] to reach the so-called Smart Factory (SF). In a SF, activities like real-time data collection enable that the access to manufacturing relevant information, anytime/anywhere, become a reality. This is done without affecting other systems, maintaining their capabilities of accomplish their tasks based on information coming from physical and virtual worlds. In addition to this, SF is capable of reacting to disturbances in production using available information to build the context under which a specific situation is occurring and taking advantage of decentralized approaches (either on information and communication) for appropriate reaction [13]. This behavior requires a high degree of synchronization between digital and real world which is being implemented. New ICT developments are providing the needed real-time access to sensors and devices as well as the advanced networking and processing capabilities contributing for an active cooperation of all the components building a sort of factory "nervous system" [15, 16]. Some implementations have been developed to support interoperability of Internet of Things systems, and, more to it, to allow search and detect both IoT and real-world resources as well as their associations [17]. The virtualization of resources contributes for reducing the complexity of internal operations, as well as generates an agile environment through the possibility of implementing decentralized decision-making approaches [2, 18].

2.3 Data Collection and Data Collection Frameworks

In the context of real-world resources, data collection, also called data acquisition or data sensing, deals with the collection of data (actively or passively) from the device, system, or as a result of its interactions [19]. For data collection, critical information needs to be available at the right point in a timely manner, and in the right form. The main aspects of a data collection system are: (i) Communication with distributed devices: This can be done over wired or wireless links to acquire the needed data, and need to respect security, protocol, and application requirements; (ii) Nature of acquisition: It could be continuous monitoring, interval-poll, event-based, etc.; (iii) Frequency: This depends on, or is customized by, the application requirements (or their common denominator). In simple scenarios, due to customized filters deployed at the device, a fraction of the generated data may be communicated. In more sophisticated scenarios, data aggregation and even on-device computation of the data may result in communication of events (such as detection of faults), which can be detected based on a device's own intelligence and capabilities [20]. IoT devices interactions and cooperation capabilities are likely to create large amounts of data [21]. This type of platform can be classified considering three different areas, namely: communication, transformation and data storage: (i) Communication: depending on the types of protocols used for sending/receiving data; (ii) Transformation: related with the techniques used to enrich data (e.g., taking into consideration the context under which this data is being collected) and how to make it more meaningful; (iii) Data storage: defining the type mechanisms used to store structured and unstructured data.

The analysis of the state of the art allows concluding that having a consistent strategy for interoperability is fundamental to guarantee the proper operation of any system involving different components as it ensures that component interfaces and shared or exchanged data are completely understood, to be interpreted by other components or systems.

3 C2NET Interoperable Data Collection Framework

C2NET project aims at facilitating the collection and usage of scattered, heterogeneous, and sometimes ambiguous, data. For this reason, interoperability is a key feature of C2NET platform which is composed of different components that are dependent on other legacy software. The developed interoperability framework acts as a middleware between C2NET components and legacy systems, not only for data collection, but also to guarantee data exchange inside the platform and provide configuration features to ensure generic usage of components. The Data Collection Framework (DCF) is the domain module that acts as the C2NET entry point of data that is arising from companies' side (see Fig. 1).

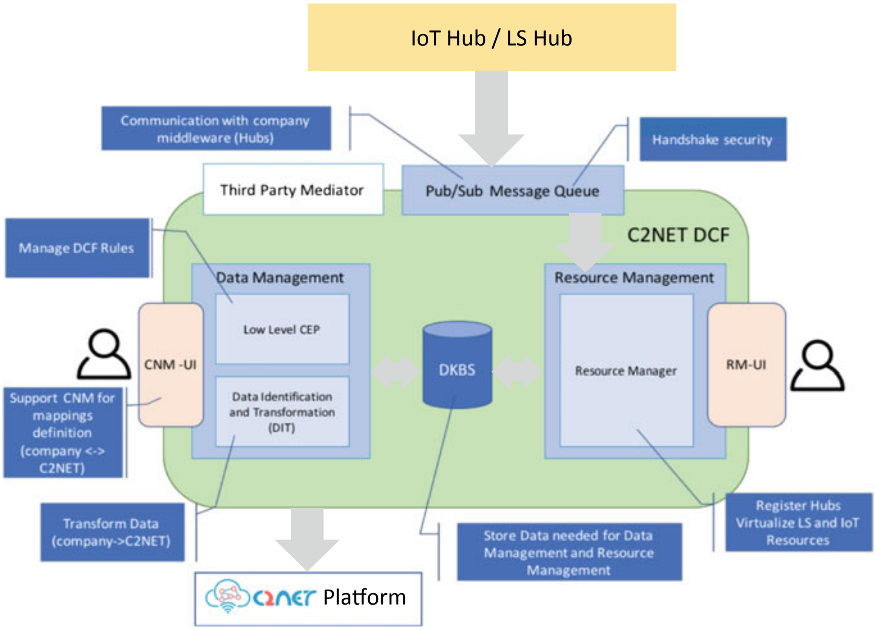

Fig. 1 C2NET data collection framework architecture

The company middleware composed by IoT and Legacy System (LS) Hubs provides the facilities required to scale the solution to any number of external resources and ensures interoperability with different data sources from ERP Systems, company databases, IoT devices, etc. To cover these aspects, three levels of interoperability have been defined for the C2NET DCF: (1) At Hubs level: where data are primary gathered from the company to the platform. Here, interoperability issues such as communication protocols, software interfaces, or data selection functions needs to be handled; (2) At Platform level: where the components are exchanging and using data from the Hubs. Here, interoperability issues such as data structures integration/mapping and transformation needs to be handled; (3) At User level: where the data can be presented to the user. This paper focuses on the first two aspects, namely:

- **Interoperability Support at the Hubs Level**: At the hubs level, there are two questions that interoperability tries to respond. The first is how to provide an interface to the hubs allowing plug and play and rapid deployment. The second is how data can be gathered intelligently to the platform, in a way that huge data flows and unnecessary information cannot affect the functioning of the system or abuse of system resources. The C2NET solution to these issues relies on the development of a secure layer able to interact in an easy and generic manner with the hubs in charge of data collection. In this way, all interfacing complexity with IoT and legacy data systems is hidden to C2NET platform. In what regards the C2NET Data Collection Framework architecture, the two main modules that are on charge of this level of interoperability are the PubSub module (responsible for the communications with companies' hubs) and the Resource Management module (provides the necessary configuration facilities for C2NET resources).

- **Interoperability Support at the C2NET Platform Level**: At the C2NET platform level, interoperability is handled from a classical enterprise information systems data interoperation problem. In technical interoperability, as the one implemented at the Hubs level, consensus between different vendors often relies on standards (e.g., communication protocols). In the case of data interoperability, standardization or the use of reference models can also be applied. C2NET applies the unified approach to interoperability. This approach consists in using a common format at a meta-level which provides a means to establish semantic equivalence, allowing consistent mapping between input and output models. Therefore, in C2NET, the unification requires a common structure at the meta-level for data to be exchanged between the different resources and C2NET platform (and its components). This is a big challenge for the modules implementing this feature because of the complexity of the task, which includes data processing and transformation. Data transformation aims to keep a common representation for collected data by providing a common structure called C2NET format.

4 C2NET to Detect Non-conformities and Reduce Waste

Production and product quality is an area of growing relevance for both manufacturers and consumers. Companies want to reduce the number of non-conformities to reduce the production costs, both by reducing the raw material that may be misused (and turned into waste), as well as to reduce the time spent in production. Additionally, increased public awareness on environmental sustainability and the rise of prices of non-renewable raw materials are contributing for market changes [22]. From a company point of view, in an ideal scenario, non-conformities and waste should be eliminated reaching a zero-defect production process. C2NET solution uses IoT in production lines to enable real-time quality control allowing the detection of non-conformities in an early process stage and contributing for waste reduction. The use case involves a Portuguese metalworking SME company that produces a huge variety of small pieces for different customers. Most of production data are scattered across different systems and in heterogeneous formats (manual registries are still common). To overcome these difficulties, the collection of data and its transformation in C2NET format were crucial to enable its usage. To support the implementation of this use case, a set of steps were defined (see Table 1).

Table 1 Use case steps

Nº	Name	Description
0	Install company resources	Preparatory phase includes identification of data sources, additional instrumentation added (if needed), installation of hubs and setting up of IoT communication network.
1	Company resource virtualization	Available resources and data collection rules are registered and configured in C2NET
2	Define C2NET mappings	Data to be collected is mapped to C2NET data format - STables
3	Define rules for non-conformity detection	Definition of rules that translate the quality patterns and allow the detection of non-conformities
4	Upload Production Order	Production order is uploaded via Legacy System Hub
5	Start Production	Production start is detected via IoT devices which reaches C2NET platform through the IoT Hub
6	Monitor the various stages of production	Production data is collected via IoT Hub
7	Detect Non-Conformities	IoT Hub collects data that triggers a non-conformity rule
8	Check production order status	The status of the production order is stored (to be resumed later if production stops)
10	Notify about Non-Conformities	C2NET sends message to production manager informing about the detected non-conformity
11	Stop production (if needed)	In critical cases production may have to be stopped
12	Setup Machine	These steps are performed out of C2NET
13	Solve Non-conformity cause	
14	Separate non-conform products	
15	Catalogue non-conform products	The non-conformity is registered together with the actions developed to solve it

LOOP

Note that, steps 3 to 6 occur continuously up to the detection of a non-conformity. (LOOP). Also, steps 12 to 14 are not processed with the support of C2NET

5 Validation and Discussion

To support the evaluation of the business impact, a set of Key Performance Indicators (KPIs) were defined. These KPIs allow the confirmation of the benefits achieved by the involved company through the use of C2NET. KPIs are associated with a number of measurable indicators to facilitate the extrapolation of information. Table 2 presents the set of KPIs defined for this use case together with the measurable indicators that will be used to evaluate each one of them. KPIs were measured in the beginning of the project, and final measurements were made at the end of the project for comparison.

Table 2 Business KPIs for metalworking use case

KPI	Associated measurable indicator(s)	Initial value	Current value
Increase in machinery availability	Average No. of stops (per 10,000 units)	16	14
	Duration of stops (per 10,000 units)	1 h 23 m	1 h 15 m
Increase in machinery working hours	Production time (pieces/hour)	8604	9158
Decrease in non-conform product	Average % of non-conform products	0.90	0.87

Table 3 Functional/technical measurable indicators for metalworking use case

Functional/technical indicator	Initial value	Current value
No. of devices installed to collect production data[a]	2	13
No. of hubs installed at company to import data	0	2
Amount of data samples being collected through IoT devices[b]	0	~2.5 KB/min
No. of existing legacy system data files (ERP)[c]	3	5
No. of existing datasets	81	92[d]
No. of imported/mapped datasets (this use case)	0	13
No. of rules for automatic non-conformity detection	0	3

[a]Including: no. of products produced; temperature of painting chamber; quality of painting
[b]Measurement depends on the sending frequency being used. In this measurement, the IoT devices were configured to collect sensors data each 10 s and send the aggregated data package each minute (i.e., 6 samples/min/sensor)
[c]Containing data regarding production order; production recipes; available resources
[d]Including IoT datasets

The analysis of the associated measurable indicators allows us to conclude that there were significant improvements regarding the defined business KPIs.

In addition to business KPIs, a set of functional/technical indicators were also defined. These indicators enable the possibility to check the development status as well as to conclude about the usability of the proposed solution. Table 3 presents a compilation of the defined Functional/technical measurable indicators together with the available measurements.

The differences between initial values and current values allow detecting a consistent increase in the data being generated and used. Note that the table presents only the values related to detection of non-conformities in two specific production stations (the ones in which the testing phase is focusing). As the non-conformity detection is to be applied in other production stations, the number of rules will also increase. Moreover, and although this is parallel to the use of C2NET, the company has developed additional effort in structuring and organizing its legacy system data in order to take the most out of C2NET functionalities. An example is the growing number of legacy system data files available. These new files represent information regarding machine availability and material consumption, and the data being collected there will contribute for a decrease in the time spent in production planning.

6 Conclusions and Future Work

C2NET project is providing an interoperability solution through a cloud-based platform for managing the company interactions and promoting enterprise interoperability. The Data Collection Framework here presented for collecting and managing data is an example of the work developed. The collection and integration of data from multiple sources in a Portuguese metalworking SME are providing an interoperable solution for additional insight into the processes. The results being obtained, even in early stage, demonstrate clearly the potential of the approach.

Future work includes the addition of virtual resources to combine collected data being generated and generate additional information and knowledge about the production operation. Also, more features (e.g., negotiation and optimization) of the C2NET platform could be exploited to enrich the interactions between the company networks. Moreover, the expansion of the approach to cover all production stations of the company, as well as to implement it in other sectors, is also planned. Some ideas will be explored in BOOST 4.0 project.

Acknowledgements The research leading to these results has received funding from the European Union H2020 projects C2NET (FoF-01-2014—nr 636909) and BOOST 4.0 (ICT-15-2017).

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