Cross-Factory Information Exchange for Cloud-Based Monitoring of Collaborative Manufacturing Networks

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***Abstract*—Cloud-based platforms and ecosystems are widely considered as a means of supporting collaborative manufacturing networks (CMN) among companies and, in particular, manufacturing SMEs. Due to the spatial separation of manufacturing activities among the CMN partners, there is a need for monitoring and coordinating the collaborative manufacturing processes. However, little research investigates inter-enterprise information exchange systems required for such monitoring and coordination. This paper proposes an approach for cross-factory information exchange considering connectivity and interoperability between various factory data sources and cloud-based collaborative production monitoring services. The paper also introduces a cross-factory information exchange mechanism, meta-models, and architecture to facilitate the ad-hoc, target specific data exchange and addresses SMEs' adoption barriers, namely trust, security, data control, and integration efforts. A proof of concept of the proposed approach is presented.**

***Index Terms*—CMN, SMEs, monitoring of collaborative processes, production meta-model, factory connectivity**

I. Introduction

Many manufacturing SMEs (Small and Medium-Sized Enterprises) are challenged by market volatility, increasing demand for customization despite mass-production, emerging technologies, and global competition. To face these challenges, collaborative manufacturing networks (CMN) have been proposed to help SMEs collaborate to reach the critical size and acquire the necessary competencies. In the context of this paper, CMN refers to an inter-organizational model that aims at establishing a dynamic network and temporary partnership among independent manufacturing companies in order to collaborate and share core competencies, exploit market opportunities, and dissolve once the goal has been accomplished [1]. A CMN is mainly driven by distributed production activities; therefore, coordination and monitoring of the manufacturing processes at the inter-enterprise level is required.

The motivation of this paper is to support the monitoring and coordination of CMNs' manufacturing processes by enabling information exchange between companies. Therefore, the paper proposes a cross-factory information exchange architecture that enables connectivity and interoperability between cloud-based production monitoring tools and the factories of the collaborating SMEs. The paper also introduces a data sharing mechanism that allows SMEs to negotiate the information to be exchanged with a cloud-based production monitoring tool. In order to support interoperability, the paper introduces a meta-model for representing, first, the collaborative production process and, second, the data to be exchanged between the cloud-based collaborative platform and the collaborating parties. The proposed solution targets SMEs; therefore, the following adoption barriers are taken into consideration as constraints on the system design: trust, security, privacy, data control, and integration efforts [2], [3].

The paper is organized as follows: Section II highlights the functionalities of the proposed architecture and describes its main components. Section III describes the implementation of the proposed system. Finally, section IV illustrates the designed architecture in an exemplary use case.

II. Cross-Factory Information Exchange Architecture

The goal of cross-factory information exchange is to support the communication and interoperability required by cloud-based collaborative production monitoring tools. To achieve this goal and understand its underlying requirements, focus group interviews with SMEs and platform tool developers were undertaken and the following high level system requirements were identified:

- Providing connectivity between on-premise factory data sources and the collaborative platform.
- Supporting service integration by defining a data exchange mechanism that enables the tools available in the collaborative platform to describe the information that is required for monitoring manufacturing processes.
- Providing a meta-model that describes collaborative manufacturing processes to enable semantic interoperability across companies.

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- Implementing the necessary functionalities to enable the aggregation and mapping of local data sources to the information needed by the collaborative production monitoring tool.

In addition, a successful information exchange approach will need to adresss the barriers present within SMEs against the adoption of such an information exchange solution. Based on a literature review of SMEs' adoption barriers and interviews with SME representatives, the following constraints were identified: trust, security, data control, and resources available for integration efforts.

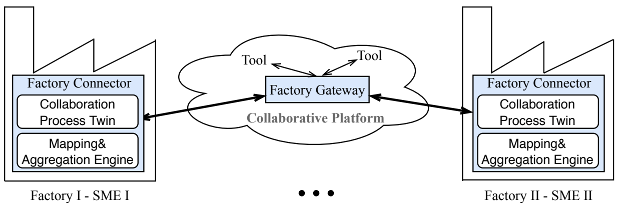

Fig. 1. Cross-factory information exchange concept

To address data control concerns, the cross-factory information exchange concept aims at minimizing the amount of data shared to information that is relevant in the context of a CMN and that the collaborating partners are willing to share. In other words, no information is shared without the explicit consent of the Factory Engineer (FE), thus enabling information control and ensuring an appropriate abstraction level. Trust is supported through on-premise data control and reinforced through transparency via the open protocols that are used. Security is provided by using standard protocols for communication which provide generally accepted security mechanisms for data in transit and allow auditing of the communication process (the security of the data at rest is covered by the platform and is outside the scope of this paper). Reducing integration efforts and resource requirements is especially emphasized in the proposed concept, as it allows a self-contained solution that provides the necessary functionalities via an easy-to-use user interface for cloud-based service integration. The cross-factory information exchange architecture comprises four components:

- **Information Exchange Mechanism** describes the information flow and processes used in the cross-factory information exchange.
- **Factory Connector** (FC) is an on-premises extension of the cloud platform that permits sharing local information with the platform.
- **Factory Gateway** (FG) is a cloud-to-edge communication component that manages the information exchange between various FCs and the platform tools.
- **Production Data Model** (PDM) is a meta-model to describe collaborative manufacturing activities and exchange information about (i.e., monitor) their progress, enabling interoperability at the inter-enterprise level and supporting the architecture's information exchange mechanisms.

A. Information Exchange Mechanism

The cross-factory information exchange architecture supports dynamic information exchange, allowing the tools in the platform to specify requests for the information they require. These requests are attached to an instance of the PDM (for example, a request to provide progress information is added that references one of the production activities modeled) that is relayed to the FE who then decides on a case-by-case basis to accept or deny the requests. The communication endpoints for the information exchange are the FC and the FG, which between them help bridge the gap between industrial automation and cloud-based communication protocols.

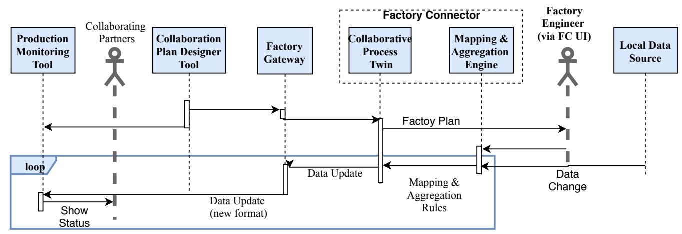

Fig. 2. The negotiation process for dynamic data requests

The process – as shown in Fig. 2 – can be described by the following three phases:

- Installation: The FC is received and locally installed by the FE. Appropriate steps are taken for each FC being specifically configured for one site – the location where manufacturing operations take place, usually a factory.
- Configuration: This phase starts with specifying and agreeing on a collaboration plan – modelled according to the PDM. The selected tool adds the required data requests ("dynamic data requests") for monitoring and coordinating the collaborative production process. The manufacturing plan specific to a site (the "factory plan") is then sent to the FC and stored locally. The FE then decides which of the dynamic data requests to answer and configures the FC through its UI accordingly.
- Transfer: The FC sends updates corresponding to the previously accepted dynamic data requests. Upon receiving a new factory plan, the configuration phase starts again.

B. The Factory Connector

The FC forms an on-premise endpoint of the collaboration platform, supporting the collection and preparation of data for platform tools. The FC is pre-configured with site-specific information to authenticate and securely connect to the FG. The FC listens for Factory Plans and adds a representation of them to the collaborative process twin. The FE then collects, aggregates, and maps the appropriate local data sources to answer the requests. The status updates are then sent to the FG. The FC has two components:

- The Collaborative Process Twin (CPT) acts as a digital representation of the aspects of the Production Plan that are relevant to the collaborative manufacturing project. The CPT stores the Factory Plans corresponding to the

various CMNs that the factory is involved in. It then provides a representation of the collaborative manufacturing activities and dynamic data requests that the factory is committed to and stores the latest manufacturing status updates that are subsequently sent to the platform.
- The Mapping and Aggregation Engine (MAE) supports the FE in the collection and processing of local factory data so that it matches the syntactic and semantic requirements of the dynamic data requests. This is done through the MAE's user interface which allows the FE to first select specific local data sources, then aggregate and map the collected data to the corresponding dynamic data requests in the CPT.

C. The Factory Gateway

The FG manages the encrypted bidirectional communication between the FCs and cloud-based tools and serves as an endpoint for the platform. The FG ensures syntactic interoperability [5] of the status updates provided by the FC as well as the collaboration plans created in the tool. The FG is also responsible for routing the messages between the respective FCs of the collaborating partners and the corresponding tools. Upon receiving Collaboration Plans, the FG extracts the Factory Plans for each specific site and sends them to the corresponding FCs. During the data transfer phase, the FG receives the status updates from the FCs, converts them into the platform-specific format, and sends them to the appropriate tools.

D. The Production Data Model

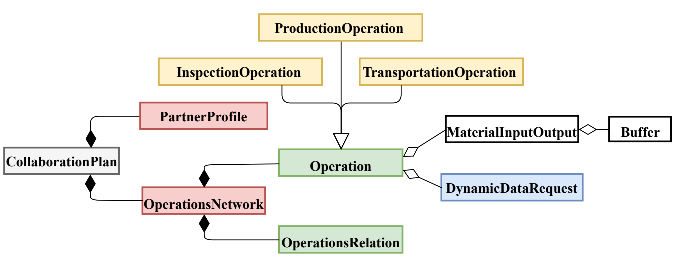

Fig. 3. Simplified UML class diagram of the Production Data Model

The production data model is designed to support interoperability of the cross-factory information exchange. The PDM is inspired by the ISA-95 standard [7] which provides a generic view on manufacturing operations and models production processes, resources, and the relationships between these elements. Therefore, the PDM draws on them for a generic classification of manufacturing operations, related material, and equipment. However, the ISA-95 standard focuses on vertical integration within a single enterprise; therefore, the PDM extends the modelling capabilities of ISA-95 with collaborative network concepts. Its structure is tailored towards monitoring and coordination of collaborative manufacturing processes between individual companies.

Fig. 3 provides an overview of the PDM. The "CollaborationPlan" class wraps the whole model, representing the collaborative manufacturing plan and the companies involved. The collaborative manufacturing plan, represented by the "OperationNetwork" class, is composed of set of operations and relations that link them. An operation can be of different types: production, inspection, and transportation. To monitor the material flow in a process, the PDM provides a way to model the input and output materials for an operation, as well as the storage used for the materials. This allows to track the quantities of materials at each operation, if necessary. To enable the coordination of the collaborative manufacturing plan, the PDM models the relations between the operations and specifies conditions that govern how the operations are triggered. Once the "CollaborationPlan" is defined, cloud-based tools add information requests to each operation where data updates are required. These requests are instances of the "DynamicDataRequest" class and include a semantic and syntactic description of the information required.

III. Proof-of-Concept Implementation

The cross-factory information exchange architecture has been implemented in the context of DIGICOR, a European research project for the development of an Industry 4.0 cloud-based Collaboration Platform. The DIGICOR collaborative platform is an open ecosystem which provides a pool of collaborative tools and services available in a tool store (marketplace). The DIGICOR platform supports the CMNs' lifecycle while providing security mechanisms and governance rules. The cross-factory information exchange architecture extends these core platform mechanisms with an additional layer of data minimization and control at the edge.

The DIGICOR platform architecture is event-driven and service-oriented. The security of the DIGICOR platform is based on access and usage control, attribute based encryption, and digital rights and identity management. The service instances are clustered using Docker on Amazon Web Service instances. Their deployment is managed by Kubernetes. Data is exchanged between FC and FG over AMQP 1.0 with TLS encryption using an AWS managed ActiveMQ message broker instance, following a publish/subscribe pattern. Since Industrie 4.0 standardizes on OPC UA as its communication protocol, the FC CPT was modelled as an OPC UA address space in order to blend naturally with other shop floor data sources. Consequently, communication from the FC to the FG follows the OPC UA PubSub specification (with JSON encoding).

A. The Factory Gateway

The Factory Gateway is implemented in Java, using the same build and execution environment as other DIGICOR platform tools. It consumes and publishes the required events from/to the Event Store and acts as an AMQP publisher, sending Factory Plans to the corresponding FC, and as an OPC UA subscriber, for receiving status updates from the FC (via OPC UA PubSub over AMQP). Each message received from a DIGICOR tool or the FC is first converted to the appropriate representation by translating the OPC UA PublishedDataSet to DIGICOR events and vice versa, then routed either to the corresponding FC or the appropriate DIGICOR tool.

B. The Factory Connector

The FC is written in Java and JavaScript for operating system independence. The FC is pre-configured with a connection to the FG. The Factory Plans are sent to the FC over AMQP via a predefined queue. The FC listens for Factory Plans, mapping received plans to the OPC UA address space of the CPT. The FE then uses the MAE to connect to local factory data sources, using subscriptions within the OPC UA client/server model. Through its UI, the MAE allows the FE to aggregate the collected data (via builtin functions such as counters as well as fully custom Javascript functions) and then map it to the requested data. Thus, whenever the value of a factory data source changes, the defined aggregation function is triggered, and the new value is mapped to the corresponding event field in the CPT. The CPT is implemented using the Eclipse Milo OPC UA stack.

IV. Use Case Scenario

The use case introduced in this section synthesizes various scenarios encountered by the authors. The use case assumes a CMN composed of four SMEs collaborating on manufacturing an aircraft lavatory. After the phases of successfully selecting the adequate partners, forming the CMN, securing the tender, and designing the product (all of which would usually be supported via tools in the collaborative cloud-based platform), the execution phase begins. Using a tool for designing the manufacturing plan, all partners collaborate and create a collaborative plan, which models the network of manufacturing operations for producing the desired aircraft lavatory at the agreed-upon abstraction level while focusing on activities that are considered as critical by the partners and would require monitoring. To monitor and coordinate the collaborative manufacturing process, a production monitoring tool, available in the collaborative platform marketplace, is purchased by the CMN. Fig. 4 illustrates the collaborative manufacturing process agreed upon by the collaborating partners. Depending on the industrial systems available at each SME, the information to be shared can be obtained from different data sources. The frequency of sharing information can also be defined for each specific case.

To simulate the data sources of SME2 in this use case, a partial OPC UA server address space for the controller of the machine tool that would be used for making the moulds was implemented, following the OPC UA Information Model for CNC Systems [9]. The server address space contains the name of the control program (manufacturing job) currently executed, which together with the program execution status is used by the MAE as an indication of progress relevant to a specific CMN related activity. The FC runs on a separate embedded PC, providing the link to the production monitoring tool via the FG. A browser-based juser interface gives access to the MAE.

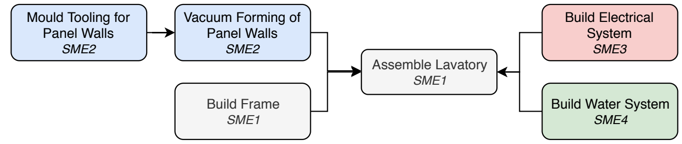

Fig. 4. Use case scenario collaboration plan

V. Conclusion and Future Work

The monitoring and coordination of collaborative manufacturing processes is instrumental to the success of CMNs. To this end, a cross-factory information exchange architecture is proposed which provides the connectivity infrastructure and data exchange mechanism between on-premise data sources and services in a cloud-based collaboration platform, allowing for remote monitoring of production activities. We also provide a meta-model that provides a common, interoperable framework for describing manufacturing activities and requests for information about their progress. The approach addresses the most critical adoption barriers for SMEs, namely trust, security, data control, and integration efforts.

A proof-of-concept implementation was established within the context of an existing collaboration platform, DIGICOR, covering an exemplary use case scenario. Further use cases and scenarios for the cross-factory information exchange architecture will be investigated to validate the design, assess the performance of the proposed solution, and estimate the SMEs' satisfaction with regard to whether the adoption barriers have been successfully lowered.

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