A Distributed Registry of Multi-perspective Data Services for the Internet of Production

(Discussion Paper)

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Abstract

Service-oriented computing is one of the key enabling technologies to enable the digital transformation of production systems, to communicate with each other and rapidly configure themselves to meet dynamic production needs. Service-oriented architectures (SOA) are also crucial to promote the horizontal integration of digital factories across multiple interleaved supply chains, forming the so-called Internet of Production (IoP). The increasing availability of services from multiple supply chains to be aggregated and composed into composite services is leading to a new service ecosystem, named Big Services. In this context, the traditional vision of service registries, with a flat organisation of services to match the mutual requirements of supply chain actors, is no more feasible. A more structured model is required, taking into account the distinction between domain-oriented atomic services, at the single actor level, and demand-oriented composite services, at the supply chain and IoP levels. In this paper, we propose the model of a distributed registry of data-oriented services in an industrial production network. The organisation of services in the registry is guided by multiple perspectives of the production network, namely: (i) the business goal of a real production network; (ii) the perspective on production data that is managed through the services; (iii) the data flow stages implemented through the services (that is, data collection, monitor, dispatch and display). The resulting portfolio of services is distributed over the production network, allowing each actor to preserve control over the owned data and enabling the dynamic composition of services at higher levels. A preliminary validation in a real case study has been performed to demonstrate the feasibility of the approach.

Keywords

Internet of Services, service-oriented architecture, Cyber Physical Production Networks, Industry 4.0

1. Introduction

Recently, the digital transformation of smart factories is evolving towards a multiple supply chains level, where actors of the production environment (e.g., production leaders, suppliers and customers) are experiencing a horizontal integration across multiple interleaved supply chains, forming the so-called Internet of Production or Cyber Physical Production Networks [1]. The ever-growing application of smart technologies, such as sensor networks, cloud computing, data management and artificial intelligence, is aimed at enabling production systems to communicate with each other and rapidly configure themselves to meet dynamic production needs [2].

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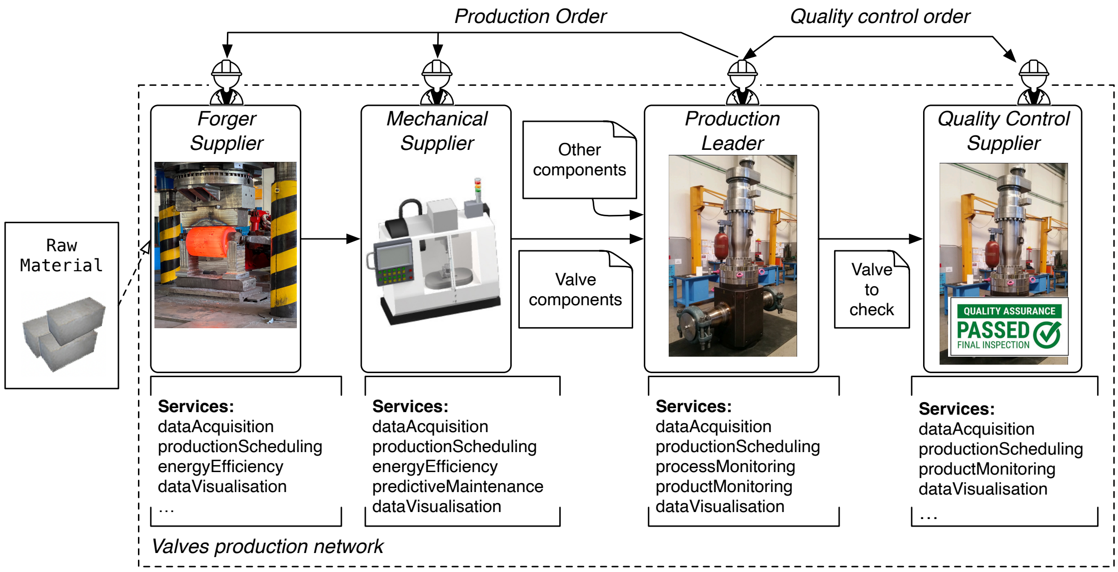


Figure 1: Actors and tasks of a deep and ultra-deep water valves production network (real case study).

Nevertheless, this vision is still far from being realised in concrete production supply chains, which are still isolated from each other and do not allow data to cross the borders of actors cooperating in the production environment. Service-oriented architectures come to the rescue, enabling modular and reusable software infrastructures, platform-independent interactions between software components and information hiding for ensuring data sovereignty in a distributed environment.

For example, let's consider the production network of deep and ultra-deep valves (Figure 1). The production of the valves as the final product, their installation on-field and maintenance are time-consuming and costly tasks. Moreover, valves are delivered on-demand in low volumes, very often designed to serve the specific needs of customers. As for many similar production networks, different categories of actors are involved: the production leader (e.g., the valves producer); the raw materials suppliers (e.g., the forger); the suppliers of mechanical processing tasks (who is in charge of machining raw materials provided by the forger to be assembled in the valves); the suppliers of specific tools used in the production stages (e.g., to perform quality tests on the valves). Actors may perform different tasks, requiring data owned by other actors and services delivered across actors' boundaries. Collaboration among them is crucial to deliver on time high quality products. For instance, the production leader of a supply chain is interested in the optimisation of the production scheduling, which involves all actors. Therefore, the latter task requires the leader to (partially) access data about all the production phases and this can be propagated across multiple supply chains. Knowledge about delays and their causes might be useful to all actors, but each actor should carefully dispatch only the information about his/her own machines that is strictly necessary, properly controlling data sovereignty across different chains. Similarly, energy efficiency can be ensured by acting at the multiple supply chains level, according to recent carbon footprint strategies [3].

In the considered example, different types of services can be used, with different purposes: (a) *atomic services*, which refer to local services used to access, monitor, and process data within a single actor; (b) *composite services* which involve the composition of atomic services across actors *within* and *between* supply chains, to implement domain-specific processes or to serve immediate, demand-oriented needs emerging from the supply chain customers. The increasing availability of services from multiple supply chains to be aggregated and composed into composite services is leading to a new service ecosystem, named Big Services [4]. In this context, the traditional vision of service registries, with a flat organisation of services to match the mutual requirements of supply chain actors, is no more feasible. To this aim, the contribution of this paper is the model of a data-oriented service registry in an industrial production network. In the registry, services are organised according to multiple perspectives of a production network, namely: (i) the business goal (e.g., production scheduling, sustainable energy consumption, process monitoring and product quality control); (ii) the perspective on production data that is managed through the service (e.g., the industrial assets owned by actors in the network, the product over its lifecycle, the production process); (iii) the data flow stages performed by the service (that is, data collection, monitor, dispatch and display). The resulting portfolio of services is distributed over the production network, allowing each actor to preserve control over the owned data and enabling the dynamic composition of composite services at higher levels. The paper is based on the approach described in [5]. Atomic services rely on a multi-dimensional data model already presented in [6].
The paper is organised as follows: cutting edge features of the approach compared to the state of the art are discussed in Section 2; Section 3 describes the model of the service registry; Section 4 presents the implementation architecture; the experimental evaluation of the approach in a real case study is sketched in Section 5; finally, Section 6 closes the paper.

2. Related work

Since the first stages of the Industry 4.0 revolution, service-oriented architectures (SOA) have been proposed to foster the development of platform-independent, interoperable and component-based integration of Industry 4.0-compliant devices, machines or parts of production plants [7]. SOA proved to be an efficient approach to cope with the heterogeneity of the industrial systems, to assure interoperability, reuse, standardisation and information hiding [8, 9]. SOA is also the most widely used design framework in IIoT-based application architectural designs [10]. In [11] recent approaches for handling Digital Twins have been reviewed, in order to fully understand the relationship between Digital Twins and Web Services. Further research has been performed to study the application of SOA to the multi-layer structure of the digital factory, aimed at better representing the complexity of industrial environment [12], also proposing context-aware solutions [13], service-oriented composition [14], collaborative work [15]. In [16] authors discussed the introduction of model-driven design of complex Industry 4.0-compliant plants by starting from modular components exposed as web services. An alternative proposal based on the design of production processes as workflows is described in [17]. The adoption of SOA has enabled the integration of this technology with Multi-Agent Systems (MAS). For instance, in [18] an architecture based on MAS, SOA and Semantic Web technologies for the management

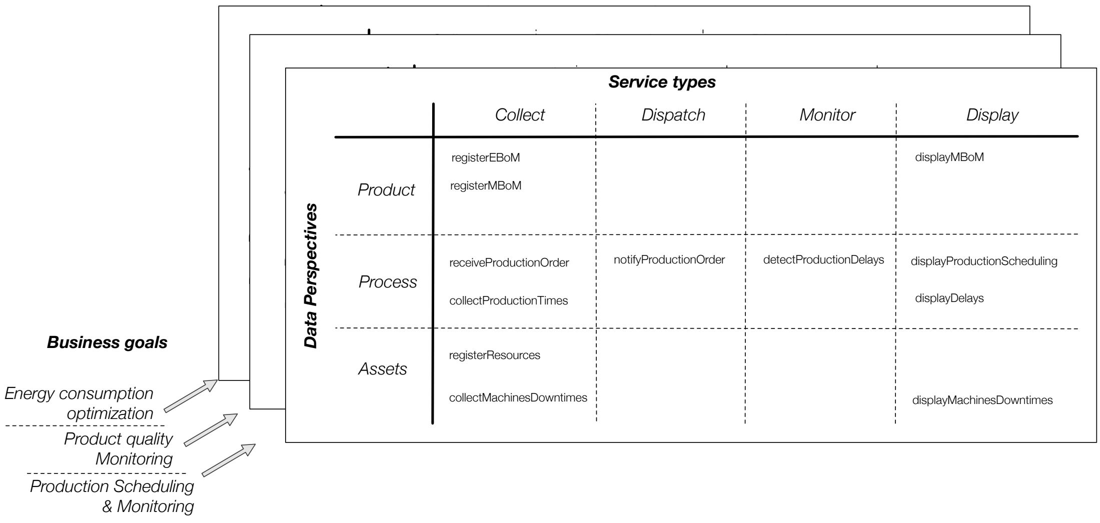


Figure 2: Multiple perspectives used to organise services in the registry.

of IIoT devices in manufacturing systems has been discussed. Existing approaches already investigated the relationship between Digital Twins and the Product Lifecycle Management [19], also introducing the novel concept of Digital Thread, intended as the cyber side representation of a product, to enable the holistic view and traceability along its entire lifecycle [20]. Nevertheless, the idea of proposing a service registry, where data services are organised according to different perspectives (namely, the three perspectives of product, process and industrial assets) and categorised with respect to the data flow within the Cyber Physical Production Network, is a winning strategy to avoid the proliferation of ad-hoc service-oriented solutions. As a first attempt in this direction, we proposed to adopt the business goal, the perspective on production data and the high level action performed by the service as criteria to organise the service portfolio within the registry.

3. Multi-perspective data service registry

A methodology to guide the design of a multi-perspective data service registry in a Cyber Physical Production Network has been described in [5]. Figure 2 highlights the three perspectives used to organise services in the registry, namely: the data model (product, process and industrial assets) introduced in [5, 6]; the business goals, identified during requirements analysis in the real case study; the data flow stages in the production network, namely data collection, monitor, dispatch and display.

Within the proposed data-oriented service registry model, the business goals correspond to composite services that can be implemented either within or across different supply chains. In the real case study, four business goals have been identified: production scheduling, process monitoring, sustainable energy consumption and product quality check. These composite services are composed by combining atomic services, managed by a single actor, specifically designed to access, share and visualize the data among all actors involved in the production network: (i) **collect services**, used by each actor to acquire data from the physical side of the production network, such as the scheduled production plan or sensor data about machine energy consumption; (ii) **monitor services**, used to detect anomalies that may lead to higher consumption or breakdown/damage of the work centers, production process failures delays or product quality issues; (iii) **dispatch services**, used to share data across the actors of the production network, such as the service to collect delivery dates from suppliers in production scheduling; (iv) **display services**, used to visualise data on dashboards or ad-hoc GUIs. Depending on the type of data that is managed by atomic services, they are further classified as product-, process- and asset-oriented.

Example. Figure 2 reports the set of atomic services used to compose a *Production Order Scheduling* service (POS, in brief) and a *Production Status Monitoring* service (PSM, in brief) in the production scheduling and monitoring business goal. The first stage of the POS service concerns the registration of the Engineering Bill of Materials (EBoM) and the Manufacturing Bill of Materials (MBoM) by the production leader, through the corresponding Collect under the product perspective. After the MBoM registration, process phases are scheduled for the product to be created (`receiveProductionOrder` Collect service) and resources are scheduled (`registerResources` Collect service). Therefore, a handshaking procedure starts (in the process perspective), where the production leader notifies the suppliers of the product parts to be assembled, according to the MBoM (`notifyProductionOrder` Dispatch service) and received from the suppliers the delivery date of each required part (`collectProductionTimes` Collect service). Finally, display services are exposed to visualise data on the process, such as the MBoM (`displayMBoM` service) and the production scheduling (`displayProductionScheduling` service). Monitoring of production advancement (PSM composite service) presents a different pattern of stages: possible downtimes are first collected from machines (`collectMachinesDowntimes` Collect service) and delays are identified or predicted (`detectProductionDelays` Monitor service). The machines downtimes and delays are sent to the production leader, who is interested in this kind of information (`displayDelays` and `displayMachinesDowntimes` services), since it has an impact on the production schedule of the final product.

Data and service access policies. In the registry, atomic services and composite ones (POS/PSM) are organised into two levels. Furthermore, as detailed in [5], the policies to manage access permissions on data and services for the actors of the supply chain are designed. The RBAC model applied in the approach considers three levels, each defining the users U, the roles R and the permissions P. At the first level, the users in the set U correspond to one of the actors of the production network. At the second level, actors are assigned to one or more roles in the set R, determining their involvement in the production network. Examples of roles are the main producer, the suppliers of mechanical manufacturing tasks, the suppliers of raw materials, and the client. This separation of concerns eases the management of complexity in interleaved production networks, where a single actor may be involved in different networks, being a main producer in one of them and a supplier in another one. A permission $p_i \in P$ identifies which object and what properties/fields of the object can be accessed, by which actor and what is

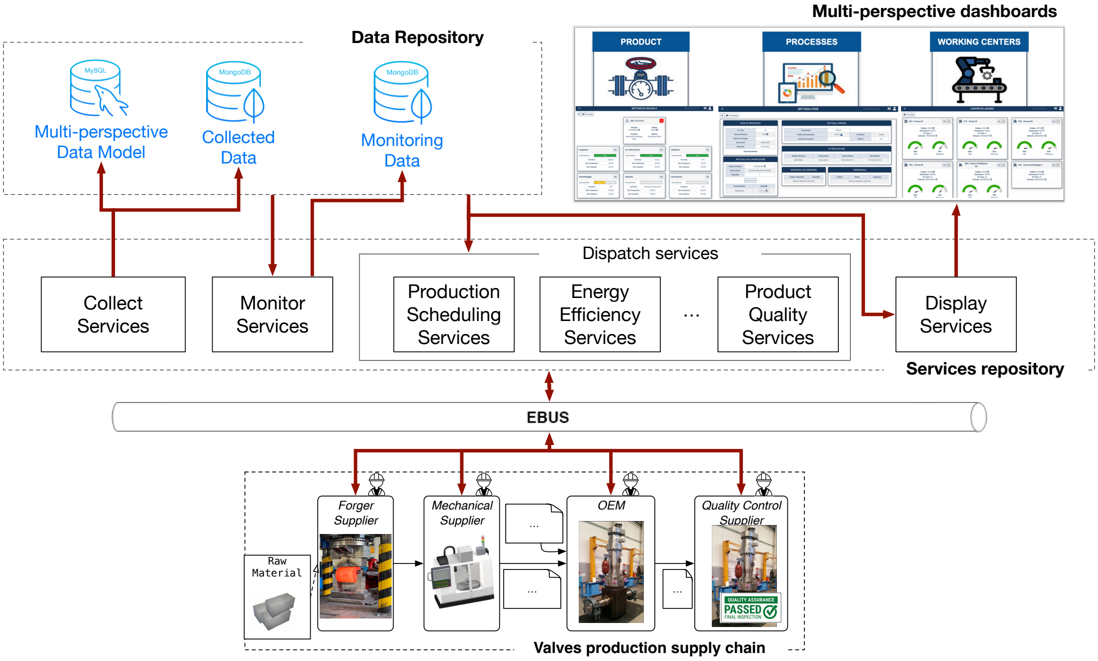


Figure 3: Service-oriented architecture for Cyber Physical Production Network in deep and ultra-deep valves production.

the allowed operation on the object and its properties/fields (in terms of CRUD actions). Each actor must have access only to the data and services for which he/she is authorised, i.e., related to his/her own internal company performance and his/her role in the production network. For what concerns the invocation of collect and dispatch services, according to the sequence diagram that models the interactions between actors, token-based mechanisms (e.g., OAuth) can be adopted. Monitor services process collected measures, under the three perspectives, and raise alarms/warnings in case of values overtaking predefined thresholds or in case of concept drifts in the data streams. These warnings/errors are properly notified to target actors identified at design time (e.g., a problem on a work center may be notified to the owner of the machine, while a delay on a process phase execution may be notified to the actors responsible for the phase and possibly to the main producer). Regarding display services, they are provided through a web-based dashboard which incorporates authentication and authorisation mechanisms for users.

4. Implementation architecture

Figure 3 presents the architecture that implements the service-oriented approach described in this paper, including the four business goals introduced in the previous section. In the architecture each actor is equipped with (i) his/her own vision of the data that the actor can explore (*data repository*), organised according to the multi-perspective data model; (ii) a list of services the actor has at his/her disposal to interact with internal industrial assets or machines in the form of Cyber Physical Systems and a list of services exposed by the other actors (*service registry*); (iii) a web-based *multi-perspective dashboard* for data exploration and visualisation purposes. The data repository includes both structured data, stored within a relational database according to the multi-perspective model and semi-structured data, stored within a MongoDB NoSQL installation (*Collected Data*).

MongoDB database stores fine-grained measures collected as a continuous flow of data (data streams) from the production network (e.g., sensors data acquisition). For each measurement, a JSON document is registered, reporting the value of the measure, the timestamp, and the ID of the target entities. The data stream collected from a vibration sensor on a specific work center or component is an example of this kind of parameter. JSON documents can be organised in different collections with respect to the physical parameter that is being measured (vibration, electrical current, temperature). Fine-grained processing data can be collected internally, from resources and industrial assets owned by the actor, or externally, provided by the other actors.

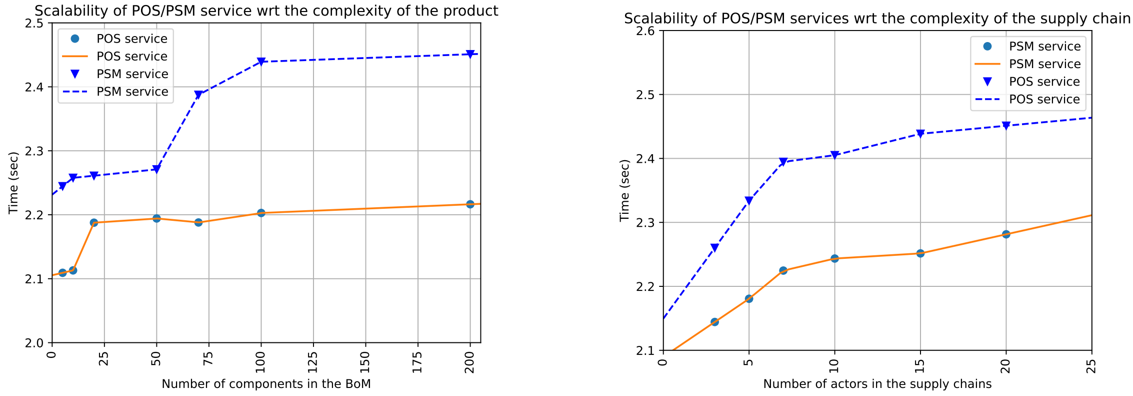
Display services populate the *web-based multi-perspective dashboard* that each actor uses for data exploration. From the home page of the dashboard, it is possible to start the data exploration by following one of the three perspectives, namely, product, process and industrial assets. Each perspective brings to a UI component (tile) implemented using ReactJS libraries: i) the *product synoptic* tile allows exploration from the product perspective of each single actor; ii) the *process phases* tile allows exploration from the process perspective of each single actor; iii) the *working centers* tile allows exploration from the industrial asset perspective of each single actor. More details on the web-based multi-perspective dashboard can be found in [5].

5. Preliminary evaluation

The evaluation of scalability has been carried out in the context of an industrial research project, where business goals have been identified. In particular, tests have been focused on POS/PSM services, aimed at registering a production order in the database of the production leader and monitoring the production order progress over the supply chain, respectively. Such services have been chosen due to their complex business logics in terms of executed operations and interactions between actors in a supply chain. In the experiments, response times have been measured for the aforementioned services by varying (in terms of the number of units) a pair of factors that may hamper service scalability: (a) the complexity of the product, represented as the number of components within the product Bill of Materials (BoM); (b) the complexity of the supply chain, intended as the number of actors involved in the production process. Results are shown in Figure 4.

The experiments have been run on a PC equipped with Windows 11 Home, AMD Ryzen PRO 4650U, RAM 8GB. Services are based on the multi-dimensional data-model presented in [5], implemented using a MySQL database. Both the data layer and services have been implemented through the Laravel framework, an MVC framework for Web applications development which also includes an ORM for built-in support for database management systems. Services have been exposed as RESTful services. For tests, the invocation of services has been performed with a Python script sending HTTP requests to the RESTful APIs of services.

Figure 4(a) reports response times of the POS and PSM services, by varying the number



(a)

(b)

Figure 4: Response times in scalability experiments.

of components of the product BoM. The performance of the service-oriented architecture decreases as the number of components increases, but scalability is preserved. In particular, in the experiments, it has been observed that the response times are upper bounded by the complexity of the supply chain, more than the number of components in the BoM. On the other hand, as demonstrated in Figure 4(b), as the number of actors increases, the POS and PSM services still remain scalable.

6. Concluding remarks

In this paper we propose the model of a registry to organise data-oriented services in a production network, according to different perspectives, namely: (i) the business goal of a real production network (e.g., production scheduling, sustainable energy consumption, process monitoring and product quality control); (ii) the perspective on production data that is managed through the service (e.g., the industrial assets owned by actors in the network, the product over its lifecycle, the production process); (iii) the data flow stages implemented through the services (that is, data collection, monitor, dispatch and display). The resulting portfolio of services allows actors of the production network to compose complex services that implement high-level goals, while also maintaining control over their owned data.
The proposed approach will be further developed to increase the standardisation level through the introduction of Semantic Web technologies to represent data on which services are built, as well as standard service taxonomies and a more in-depth investigation on domain-oriented and demand-oriented service composition, according to the newly emerging Big Services paradigm [4].

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