A Distributed Registry of Multi-perspective Data Services in Cyber Physical Production Networks

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Abstract: The advances in smart technologies, such as sensor networks, cloud computing, data management and artificial intelligence, enable production systems to communicate with each other and rapidly configure themselves to meet dynamic production needs. In this context, the adoption of service-oriented computing is aimed at enabling modular and standardised software infrastructures, platform-independent interactions between software components and information hiding for ensuring data sovereignty in a fully distributed environment. However, for a full-fledged exploitation of service-oriented computing capabilities in the Industry 4.0 production systems, the existing service design solutions still lack a clear specification of what is the data which the service relies on, what is the business goal of the service and when it is invoked within the information flow throughout the production network. In this paper, we propose the model of a registry of data-oriented services in an industrial production chain. The organisation of services in the registry is guided by multiple aspects 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 service (iii) the high level action performed by the service The modelling strategy has been conceived to properly guide service design against ad-hoc solutions, thus facilitating future service selection and composition to meet the business goals of collaborating actors. The resulting portfolio of services can be declined by each actor of the production network, leading to a distributed registry that allows each actor to preserve control over the owned data. The application in a case study has been performed to demonstrate the feasibility of the data-oriented services.

1 INTRODUCTION

The ever-growing application of smart technologies in modern digital factories, such as sensor networks, cloud computing, data management and artificial intelligence, is enhancing the integration of product design, manufacturing processes and general collaboration across factories over the supply chain, where production systems can communicate with each other and rapidly configure themselves to meet dynamic production needs (Mohammed and Trzcielinski, 2021). Research efforts on Industry 4.0 digital revolution shifted from the design of Digital Twins (as the digital counterpart of machines or parts of production plants in isolation at shop floor level) to the design of Cyber Physical Production Systems (CPPS), that is, hybrid networked cyber and engineered physical systems that record data (e.g., using sensors), analyse it using data-oriented services (e.g., over cloud computing infrastructures), influence physical processes and interact with human actors using multi-channel interfaces (Harrison et al., 2021). Recently, the Digital Twin and Cyber Physical Production Systems paradigms is evolving towards a supply chain level, where actors of the production environment (e.g., production leaders, suppliers and customers) rely on an integrated vision of the product, that travels throughout the production phases, enriching itself step-by-step with data about the process, the status of industrial assets used in the production, the outcomes of product quality control. Such a vision has been envisioned in recent literature on Digital Threads (Margaria and Schieweck, 2019) and the so-called Cyber Physical Production Networks (Hawkins, 2021). Nevertheless, it is still far from being realised in concrete production supply chains. First, current systems are still isolated from each other and do not allow data to cross the borders of actors cooperating in the production environment. Each actor can access data about his/her own production phases and industrial assets only, according to policies that are necessary to preserve data

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sovereignty. Second, existing solutions still have a monolithic organisation of data thus leading to limited control on the access policies concerning different perspectives.

Service-oriented architectures can come to the rescue for the implementation of functions spanning across all the layers of digital factories and all the phases of the product lifecycle management. The adoption of service-oriented computing is aimed at enabling modular and standardised software infrastructures, platform-independent interactions between software components and information hiding for ensuring data sovereignty in a fully distributed environment. However, for a full-fledged exploitation of service-oriented computing capabilities in the Industry 4.0 production systems, the existing service design solutions still lack of a clear specification of what is the data which the service relies on, what is the business goal of the service and when it is invoked within the information flow throughout the production network.

To this aim, the contribution of this paper is the model of a registry of data-oriented services in an industrial production network. The organisation of services is guided by multiple aspects to be considered in a production network: (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 high level action performed by the service (that is, data collection, monitor, dispatch and display). The registry is distributed in the sense that the resulting portfolio of services can be declined by each actor of the production network, thus allowing each actor to preserve a control over the owned data. A real case study has been performed. The aim is to demonstrate how data-oriented services can be fruitfully exploited over multiple perspectives.

The paper is organised as follows: Section 2 introduces the case study; cutting edge features of the approach compared to the state of the art are discussed in Section 3; Section 4 describes the model adopted for the organisation of services in the distributed registry; Section 5 presents the architecture that implements the service-oriented approach; a use case is presented in Section 6; finally, Section 7 closes the paper.

2 MOTIVATING SCENARIO

Figure 1 provides an overview of the considered valve production network. Valves are placed in prohibitive environments and, once installed, are difficult to remove and maintain over time and require high quality levels. The production of the valve as the final product, its installation on-field and maintenance are time-consuming and costly tasks and the product itself is delivered on-demand in low volumes, very often designed to serve specific needs of customers. The case study targets different categories of actors involved in this kind of production networks in the manufacturing sector: 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). In the production network, collaboration among actors is a main aspect in order to deliver on time high quality products. The production leader and the suppliers may perform different tasks, requiring data owned by other actors and services delivered across actors' boundaries. For instance, the supplier of mechanical processing tasks transforms raw materials in valve sub-parts by using computerised numerical control machines, that are specifically conceived for flexible production. This supplier is interested in monitoring the performances of the machines by implementing predictive maintenance and anomaly detection techniques. On the other hand, the same kind of supplier and the raw materials supplier (i.e., the forger) are interested in adopting energy efficient strategies on their assets, given the high cost of energy in this sector. Furthermore, the production leader is interested in the optimisation of the production scheduling, that involves all actors. Therefore, the latter task requires the leader to (partially) access data about all the production phases.

Business Goals. In the real case study considered above, four important business goals have been identified: the production scheduling, the process monitoring, the sustainable energy consumption and product quality check. Business goals, elicited in the industrial project through requirements analysis jointly performed by the consortium of partners, are briefly sketched in the following. In all goals, some recurring stages of data management, namely data collection (*Collect*), data monitoring (*Monitor*), data dispatching towards other actors in the production network (*Dispatch*) and data visualisation (*Display*) have been highlighted.

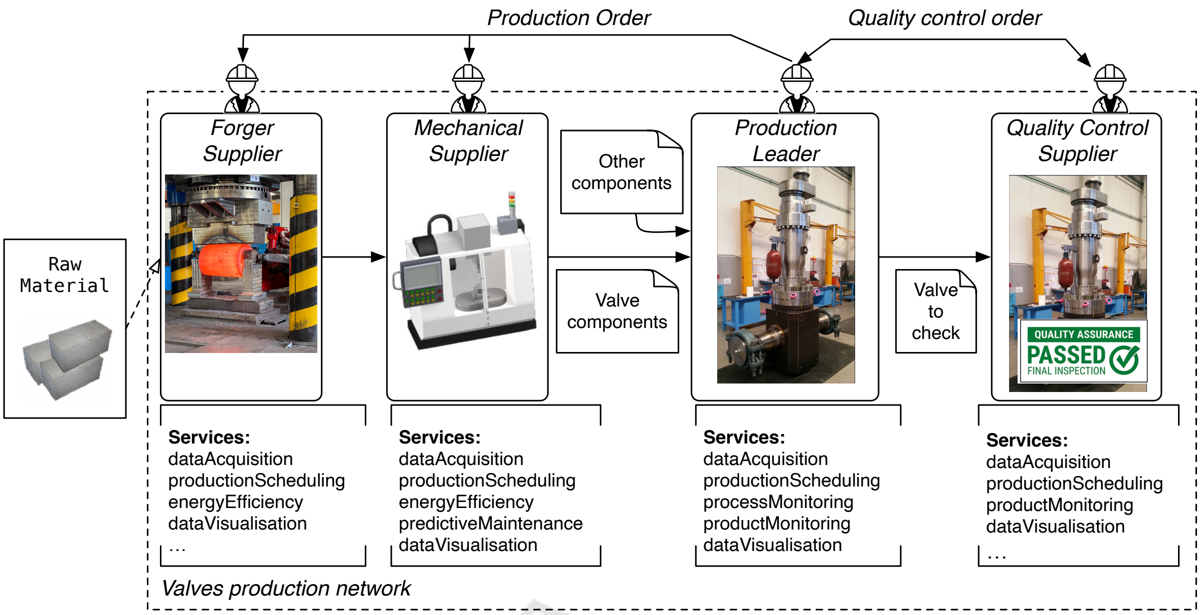

Figure 1: Actors and main tasks within the production network of deep and ultra-deep water valves, considered as real case study.

Production Scheduling. To implement this business goal, the production leader gathers from his own scheduler the data necessary to identify the product, the resources and the steps necessary for manufacturing (*Collect* stage). Once the planned production process generated by the scheduler has been received, for each planned phase the actor queries the supplier's scheduler, through the connectivity infrastructure, to receive the confirmation of the start and end date of phase execution. Each phase might concern the provisioning of raw material, the production of semi-worked components or the execution of outsourced tasks (e.g., quality controls). During production scheduling, suppliers may confirm or propose alternative dates, which are forwarded to the production leader, to perform a rescheduling, if necessary (*Dispatch* stage). As the various requests are sent by the production leader and confirmations are arriving, the progress of production scheduling is monitored (*Monitor* stage).

Sustainable Energy Consumption. In this business goal, during the *Collect* stage, each actor of the production network gathers data necessary to monitor his/her own plants from the energy consumption viewpoint. This data may be collected as sensor data directly from monitored work centers/machines (e.g., electrical energy consumption, temperature and so forth). Collected data are processed to identify possible anomalies in energy consumption (*Monitor* stage), in case sending back to monitored machines proper reconfiguration commands to reduce or limit energy consumption (*Dispatch* stage). Information about the energy consumption profiles and detected anomalies are reported on the dashboard of the owner of monitored plants/machines (*Display* stage).

Process Monitoring. In this business goal, during the *Collect* stage, each actor gathers data (e.g., times) concerning the production process phases for which the actor is responsible. Every delay that might require a production rescheduling is detected (*Monitor* stage), reported to the owner of the process phase with delays (*Display* stage) and communicated to the other actors for whom such a delay might have negative effects (*Dispatch* stage).

Product Quality Checking. During the *Collect* stage of this business goal, an actor who is interested in checking the quality of the produced product (or semi-worked component) gathers the data detected through product quality check. Collected data is processed to identify quality issues (*Monitor* stage), that are displayed on the actor's dashboard (*Display* stage), and is used to require some rescheduling and alternative executions of the production process that might (totally or partially) balance the anomalies that have been detected on products (*Dispatch* stage).

3 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 (Siqueira and Davis, 2021). SOA proved to be an efficient approach to cope with the heterogeneity of the industrial systems, to assure interoperability, reuse, standardisation and information hiding (Zhang et al., 2020; Park et al., 2020). SOA is also the most widely used design framework in IIoT-based application architectural designs (Lee et al., 2015). In (Catarci et al., 2019) 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 (Park et al., 2019), also proposing context-aware solutions (Alexopoulos et al., 2018), service-oriented composition (Derhamy et al., 2019), collaborative work (Glock et al., 2019). In (Liu et al., 2020) 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 (Kayabay et al., 2018). The adoption of SOA also enabled to combine this technology with Multi-Agent Systems (MAS). For instance, in (Cagnin et al., 2018) an architecture based on MAS, SOA and Semantic Web technologies for the management of IIoT devices in manufacturing systems has been discussed.

Contributions of This Paper w.r.t the State of the Art. Design strategies based on SOA are mainly focused on the integration of devices (or groups of devices) within the infrastructure for the development of data-driven applications. Moreover, these strategies target specific needs in the production network, such as energy efficiency (Matsunaga et al., 2022), anomaly detection (Qi et al., 2021), predictive maintenance (Nordal and E-Thalji, 2020) on work centers, production scheduling (Jiang et al., 2021) and process monitoring (Nica and Stehel, 2021). Overall, the analysis of the literature indicates that a service model that includes multiple perspectives in a Cyber Physical Production Network, namely the production process and the product lifecycle perspectives, is still an open issue. Existing approaches already investigated the relationship between Digital Twins and the Product Lifecycle Management (Tao et al., 2018), 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 (Margaria and Schieweck, 2019). Nevertheless, the idea of combining data over the three perspectives of product, process and industrial assets and designing services on top of these perspectives, properly categorised with respect to the data flow within the Cyber Physical Production Network, is missing in literature. According to our opinion, the proposal of some criteria to organise services within a registry is crucial 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.

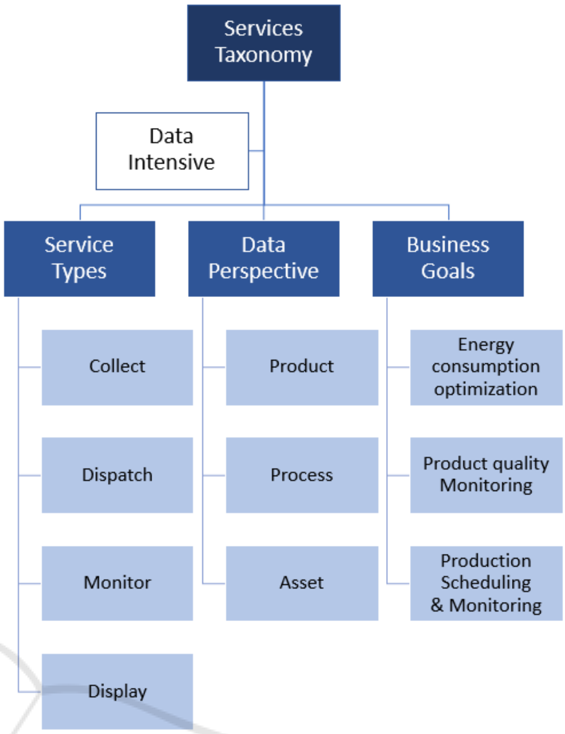

Figure 2: Classification of services according to multiple taxonomies.

4 A DISTRIBUTED REGISTRY OF MULTI-PERSPECTIVE SERVICES

In order to organise the services within the registry, in this section we introduce the service classification shown in Figure 2. The classification is driven by the three perspectives in the data model (product, process and industrial assets) introduced in (Bagozi et al., 2022), by the business goals identified during requirements analysis in the real case study and by the data

flow stages in the production network, namely data collection, monitor, dispatch and display.
Implementing business goals corresponds to the design of several services in order to access, share and visualise the data between all the actors involved in the production network. Services are mapped to the different phases of the information flow according to the actions they perform, as specified in the following:

- **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;
- **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;
- **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;
- **display services**, used to visualise data on dashboards or ad-hoc GUIs, such as the service to display the production schedule and the one to display energy consumption anomalies.

Monitor services can implement either threshold-based techniques or advanced data analysis solutions. The approach has been conceived in order to enable the integration of different data analysis models working on parameter values. An extensive discussion about such algorithms is out of the scope of this paper. Their integration within the proposed approach and their performance validation can be the object for future experiments.

We formally define a multi-perspective data-oriented service S_i as a tuple

$$S_i = \langle n_{S_i}, t_{S_i}, P_{S_i}, url_{S_i}, m_{S_i}, IN_{S_i}, OUT_{S_i} \rangle$$

where: (i) n_{S_i} is the name of the service; (ii) t_{S_i} is the service type (collect, monitor, dispatch, display); (iii) P_{S_i} is the set of perspectives on which the service is focused (product, process, industrial assets); (iv) url_{S_i} is the endpoint of the service for its invocation; (v) m_{S_i} is the HTTP method (e.g., `get`, `post`) used to invoke the service; (vi) IN_{S_i} is the representation of the service input; (vii) OUT_{S_i} is the representation of the service output. We denote with $\mathcal{S}$ the overall set of data-oriented services.

Services in $\mathcal{S}$ are implemented as RESTful services; therefore, they are also described through HTTP methods (e.g., `post`, `get`, `put` and `delete`) used in the service, corresponding to the Create-Read-Update-Delete actions on data. A multi-perspective

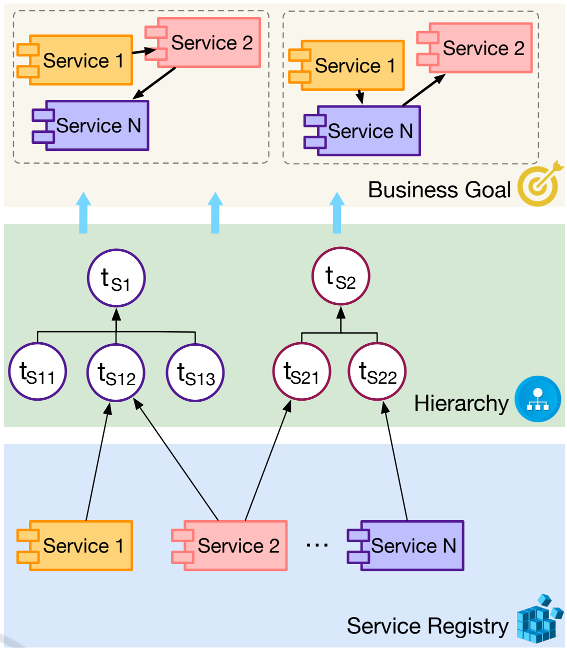

Figure 3: Service organisation within each node of the distributed service registry.

service S_i deals with different types of data, based on its input/output parameters according to the process, product and assets perspectives of the data model.

Figure 3 provides a high level view on how services are organised within the service registry. The registry is distributed in the sense that each actor has his/her own view on the portfolio of services that can be used. Business goals in the registry are conceived as a pattern of service stages and perspectives on which each stage must be focused on. This enables each actor to be guided in the selection of services according to the desired perspective and in their composition to implement a business goal following the data collection, monitoring, dispatch and display stages. Moreover, each actor can maintain control over his/her own data for data sovereignty purposes.

5 APPROACH ARCHITECTURE

Figure 4 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 on 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

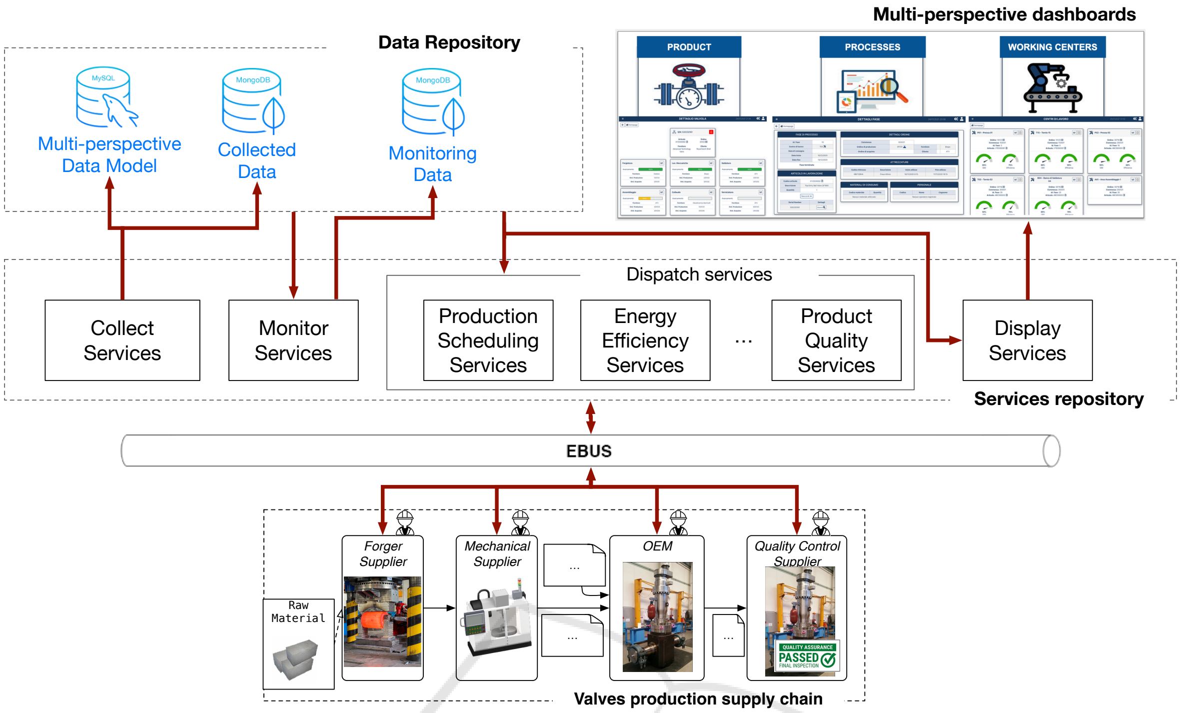

Figure 4: Service-oriented architecture for Cyber Physical Production Network in deep and ultra-deep valves production.

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, 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.

The *service registry* contains four kinds of services, mirroring the four stages highlighted in the business goals. 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 an exploration from the product perspective of each single actor; ii) the *process phases* tile allows an 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 find in (Bagozi et al., 2022).

6 USE CASE

To give a (non exhaustive) example of multi-perspective service composition to meet business goals, let us consider the production scheduling goal. The first stage in this goal concerns the registration of the Engineering Bill of Materials (EBoM) and the Manufacturing Bill of Materials (MBoM) in the data model of the production leader. These actions are implemented in the `registerEBoM` and `registerMBoM` Collect services, that are focused on the product perspective, as shown in Figure 5.

After the Manufacturing Bill of Materials of the final product has been registered, process phases are

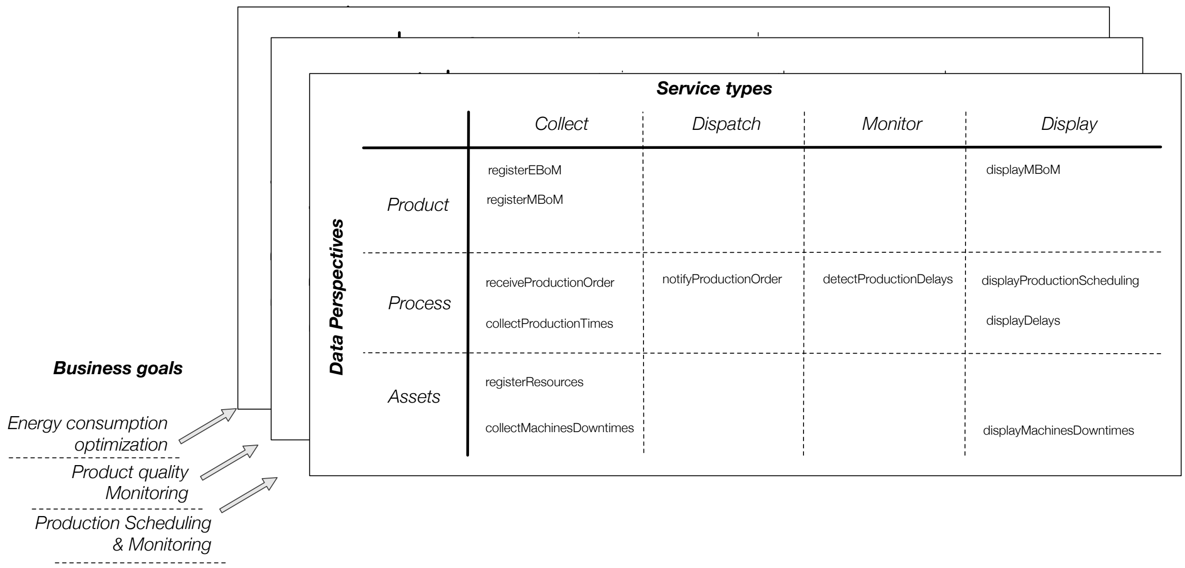

Figure 5: Multi-perspective service map: services are categorised among collect, dispatch, monitor and display services and are intersected over the product, process and assets perspectives; furthermore, services are grouped according to the target business goal.

scheduled and connected to the product to be produced and to the work centers and resources required for the production, respectively. These actions are implemented in the `receiveProductionOrder` and in the `registerResources` Collect services, respectively.

Therefore, the production leader forwards the Manufacturing BoM, the production order and resources to the scheduler for production scheduling (`notifyProductionOrder` Dispatch service). Some missing information in this schedule, concerning the delivery date of some product parts, must be asked to the parts suppliers by interacting with their schedulers, that will reply with the delivery date, returned back to the production leader (`collectProductionTimes` Collect service). This process is repeated until the final plan is obtained. Finally, display services are exposed to visualise data on the dashboard, such as the service to display the Manufacturing BoM (`displayMBoM` service) and the production scheduling (`displayProductionScheduling` service).

Monitoring of production advancement presents a different pattern of stages: possible downtimes are first collected from machines (`collectMachinesDowntimes` Collect service) and checked for the identification or prediction of delays (`detectProductionDelays` Monitor service). The machines downtimes and delays are sent to the production leader, who is interested in this kind of information, since it has an impact on the production schedule of the final product. The production leader and his/her suppliers agreed upon the services that are meant to exchange this information over the production network. Delays and machines downtimes are therefore displayed on the dashboard of the production leader (`displayDelays` and `displayMachinesDowntimes` services). The final service map for the production scheduling business goal is reported in Figure 5.

7 CONCLUDING REMARKS

In this paper we propose the model of a registry to organise data-oriented services in a production network, according to different aspects, 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 high level action performed by the service (that is, data collection, monitor, dispatch and display). The service is distributed, in the sense that the resulting portfolio of services can be declined by each actor of the production network, thus allowing each actor to preserve a control over the owned data.
The proposed approach will be further developed to increase the standardisation level through the intro-

duction of Semantic Web technologies to represent data on which services are built, as well as standard service taxonomies. The introduction of an infrastructure based on micro-services and containers as software architectural patterns will also be investigated.

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