A Workflow and Cloud Based Service-Oriented Architecture for Distributed Manufacturing in Industry 4.0 Context

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***Abstract*—In Industry 4.0, manufacturing organizations have to become more flexible and agile to stay competitive in the marketplace. Industry and academia focus on sharing globally distributed manufacturing resources and capabilities. This shift to collaborative environment calls for a service dominant logic in which reusable services model entire production processes. Accordingly, service-oriented architectures have been under spotlight by researchers to integrate distributed capabilities and resources of manufacturing. In this article, we identify rapidly developing relevant IT fields, state-of-the-art service-oriented manufacturing approaches, and discuss related challenges with those approaches. Then we introduce a higher-level workflow and cloud based service-oriented architecture for (1) individuals to design and prototype products, (2) manufacturing organizations to focus on their core competencies and find complementary services for part of their production processes, and (3) manufacturing organizations to publish their idle capabilities and resources as services. We investigate these potential impacts and more in the next manufacturing era.**

Keywords—workflow, service-oriented architecture, distributed manufacturing, cloud manufacturing, industry 4.0

I. INTRODUCTION

Enabled by a series of advancements in emerging technology domains, the fourth industrial revolution promises more flexibility and agility in manufacturing. Flexibility decreases setup times in production lines, enabling prototyping and iterative production. The ability to produce customer-driven designs changes business models and obligates manufacturing organizations to innovate [1]. To be competitive in the next manufacturing era, businesses must become more agile, responding to dynamic market situation. As a result, increasing number of organizations focus on their core competencies, and outsource complementary resources, capabilities, and expertise to other firms. The shift to collaborative environment calls for a service dominant logic where service is the application of knowledge and skills [2].

Consequently, manufacturing industry and academia increasingly focus on satisfying dynamic customer demands, sharing globally distributed resources and capabilities, higher resource utilization, and collaborative production. There has been ongoing research focusing on distributed manufacturing from information systems domain and we see these efforts as significant steps towards realizing Industry 4.0 transformations. In the literature, numerous studies investigate the applicability of service-oriented architectures (SOA) to manufacturing domain. Cloud manufacturing [3] is the latest service-oriented approach to integrate distributed manufacturing resources and capabilities into a single product service system. Cloud Manufacturing along with Industry 4.0 are considered as two major efforts shaping the next generation production systems [4]. The term Cloud Manufacturing has been around since 2010, and it received the most of service-oriented manufacturing research focus. On the other hand, problems of Cloud Manufacturing are more complex when compared to service-oriented architectures, and we discuss these problems in sections 2b and 2c. Therefore, we may not see an implementation for Cloud Manufacturing in the near future.

In this paper, we offer a higher-level architecture to deal with problems of distributed manufacturing. Our research question is how to increase utilization of geographically distributed resources and capabilities in manufacturing using a service dominant logic so that manufacturing organizations can become more flexible and agile. To answer this question, we did a comprehensive literature review, which includes goals of Industry 4.0, advancements in technology fields that lead to Industry 4.0 and service-oriented manufacturing, service-oriented approaches to manufacturing, and challenges with these approaches. From there, we used existing service-oriented approaches and latest developments in information technologies (IT) to come up with the new architecture.

After introducing rapidly developing information technology (IT) research fields that made distributed manufacturing feasible, we cover service-oriented frameworks which include agent-based systems, manufacturing grid [5], and cloud manufacturing. We bring up challenges of service-oriented manufacturing domain, and talk about why it is complicated to realize cloud manufacturing. Accordingly, we propose a higher-level workflow and cloud based service-oriented architecture to increase utilization of geographically distributed resources and capabilities in manufacturing. Using our architecture, individuals can design a workflow (flowing directed graph of tasks) and find small and medium sized enterprises (SMEs) to produce an item. Firms can also design their production processes as workflows to find subcontractors for particular tasks. After proposing the architecture, we discuss the potential impacts of a platform based on this

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architecture in the next manufacturing era. Particularly, we can speak of three contributions for this article: (1) State of the art survey for service-oriented approaches to distributed manufacturing and challenges in service-oriented manufacturing domain, (2) proposed architecture, and (3) investigation of potential impacts in Industry 4.0 context.

II. Background and Related Work

A. Background

The proliferation of distributed manufacturing requires integration of various research fields from IT. Even though contribution level of each field might differ, each research field has crucial effects on distributed manufacturing domain. In this section, we investigate these research fields, which are additive manufacturing, service-oriented architectures, cloud computing, cyber-physical systems (CPS), internet of things (IoT), and workflow management systems (WFMS).

Additive manufacturing is essential for rapidly prototyping a system or part representation before commercialization [6]. In this approach, materials are joined to make objects from 3D model data, usually layer upon layer using liquid based, solid based, and powder based systems [7]. These technologies also have different names such as 3D printing. Early use of additive manufacturing focused on visualization of the product models before production, however, more recently, it is being used to fabricate aircrafts, automobiles, mobile phones, and even fashion products [8]. Thus, individual users who want to experiment with their own product ideas can prototype their products rapidly with additive manufacturing technologies.

In manufacturing, a production process is the composition of various independent production service systems, resources, knowledge, and skills. As software engineering concepts such as loose coupling, and modularity gained importance in manufacturing, service-oriented architectures have received attention for designing production processes as services for the next generation manufacturing systems. The idea is, rather than building separate integrated systems for production processes, an organization builds a collection of services, which can be reused across all production processes. While services can be composed into higher level services to model entire processes [9], a firm can also focus only on its core competencies and depend on services from other firms for part of a production process. Thus, a number of "virtual" enterprises can work collaboratively to accomplish all manufacturing capabilities creating collaborative networked organizations [10].

Cloud computing is another area that requires attention. Cloud computing provides the tight integration of computing resources and application development platforms at lower costs. It provides a scalable infrastructure that is capable of dealing with the significant workloads across the Industry 4.0 devices. Moreover, it also helps building development platforms to implement applications for analyzing data collected from industrial devices in order to gain insight for automating and optimizing production processes.

CPS and IoT are fundamental for distributed manufacturing. In Industry 4.0 context, smart factories are mainly based on CPS, which are intrinsically connected with IoT devices. The technological advancements in IoT domain shift us toward distributed manufacturing by monitoring, controlling and optimizing the production process from procurement of raw material to distribution of finished products with the intelligent connectivity of IoT devices. This allows users of distributed manufacturing to find most suitable product line for implementing their ideas rapidly and provide feedbacks during the production process for improving the overall product quality.

Distributed manufacturing utilizes a collection of distributed resources and services, which are executed in a well-defined order to accomplish a specific goal [11]. Workflow Management Systems (WFMS) can allow managing the distributed manufacturing resources and services. It enables clients to define a workflow with the composition of distributed resources and services to schedule and simulate a set of tasks ensuring the service level agreements are met among distributed manufacturing clients and customers. Workflow modelling languages are used for modelling, analyzing, and in some cases executing processes. Popular ones are Petri net, Web Service Business Process Execution, and Yet Another Workflow Language [12].

B. Service-Oriented Frameworks for Distributed Manufacturing

In the literature, numerous studies use service-oriented approach to integrate distributed services and resources into a single product service system. The main benefits and challenges of service-oriented manufacturing is investigated in the study of Gao et al. [13]. It provides a case study to describe service-oriented manufacturing as a service innovation from business model, industry insight, and technology strength perspectives. Another study [14] proposes a web-based manufacturing resource service model to share and reuse these web-based manufacturing resources. This study mainly addresses web-based resource discovery, resource libraries and application services to demonstrate that web-based manufacturing resource service is practical for networked product development. Wang et al. [15] built a prototype agent-based workflow to model dynamic and loosely coupled internal and external business processes. Similarly, the study of Shen et al. [16] provides an agent-based service-oriented integration architecture to orchestrate and manage enterprise web-services.

Another service-oriented approach for distributed manufacturing is manufacturing grid, which operates production processes in an integrated and collaborated fashion [5]. Main idea behind the manufacturing grid approach is adopting grid computing technology to product design, manufacturing resource integration and sharing, enterprise management, enterprise collaboration, resource optimal allocation, and scheduling [17]. It utilizes the distributed resources in heterogeneous systems to create entire manufacturing processes in an integrated environment. Thus, these distributed manufacturing resources are leveraged in the form of virtual enterprises [18]. Manufacturing grid also utilizes all kind of manufacturing resources optimally and provides a cooperative work environment for personalized mass production [19].

Cloud manufacturing was inspired by emerging IT fields that are cloud computing, IoT, and CPS. There is not yet a standard definition for cloud manufacturing, but Xu defined it after National Institute of Standards and Technology's definition for cloud computing [20]. Essentially, cloud manufacturing is application of service-oriented approaches to manufacturing, however, problems to be solved are more complex when compared to problems of SOA [21]. There are certain obstacles for cloud manufacturing to be realized for which researchers have been working on, because cloud manufacturing is complicated. In cloud computing, idle resources can be rapidly provisioned and assigned when needed, and they can be released when not needed. In cloud manufacturing, cost of idle humans, capabilities, and resources are too high. Rapidly hiring & firing workforce and encapsulating skills & expertise may not be possible. We discuss the additional challenges of service-oriented manufacturing in the next section.

C. *Challenges in Service-Oriented Manufacturing Domain*

Utilization of service-oriented approaches in distributed manufacturing domain presents challenges that include service discovery, service matching, service selection, service scheduling, and service composition.

One of the most important problems of distributed manufacturing frameworks is providing an efficient and effective service discovery mechanism to determine an optimal configuration among diverse set of distributed manufacturing resources and capabilities. In the literature, several studies propose service discovery frameworks for distributed manufacturing. The study of Zhang et al. [22] proposes a service discovery method to realize the on-demand use and optimization allocation of manufacturing resources. Another study [23] proposes a four-phase method for resource service matching and searching for service-oriented manufacturing.

Another key issue in distributed manufacturing domain is semantic modeling, description of manufacturing resources, and matching these resources with manufacturing tasks & user requirements to enable on-demand resource service provision. In the literature, there are different methods for modeling manufacturing tasks and intelligent matching engines to classify those manufacturing tasks and resources. The study of Wang et al. [24] investigates these semantic description methods and matching engines in distributed manufacturing frameworks. Furthermore, there are different approaches including information modelling based and ontology based for modelling manufacturing tasks and resources. A study [25] proposes information modeling based framework to describe product-life cycle and to access, store, serve, and reuse all the product information throughout the entire lifecycle based on unified modeling language (UML) notation. However, information modelling based approaches are insufficient to provide enough information about manufacturing tasks across enterprises [24]. Thus, recent studies [26] focus on ontology based approaches to establish an intelligent service modeling and accordingly a service matching engine.

The distinctive characteristics of service-oriented distributed manufacturing reveals a vital challenge for selecting the most effective and efficient services, scheduling these services to allocate and share manufacturing resources, and optimizing the execution routes of manufacturing tasks. Goal of service selection and scheduling studies is minimizing the execution time and cost while maximizing the reliability [21]. In the literature, there are different approaches for service selection and scheduling including QoS-aware [27], energy-aware [28], or based on time, quality cost and service (TQCS) [29]. Moreover, the composition of these services is an important criterion for service selection and scheduling. In service-oriented distributed manufacturing, service composition is responsible for optimal allocation of manufacturing resources and capabilities. There are different approaches and methods [30] including Workflow-based [31], QoS-based [32], AI-based [33], Agent-based [34] and Graph-based [35] to determine the optimal service selection and composition.

III. The Architecture

In this section, we present a conceptual architecture which is structured according to SOA in order to support interoperability and loose coupling of manufacturing entities. Globally distributed entities of manufacturing value chain (suppliers, logistics, producers, micro-producers, testers) publish their capabilities as services through *Service Modeling* interface. On *Workflow Designer* interface, customer designs a workflow, which is a flowing directed graph of tasks to produce an item. Published services are matched to the nodes of the workflow and feasible compositions are generated. *Bidding*, *Optimization*, and *Agreements* are done before workflow is executed. After all these steps, execution is monitored for any violations in agreements. This process flow is depicted in Figure 1.

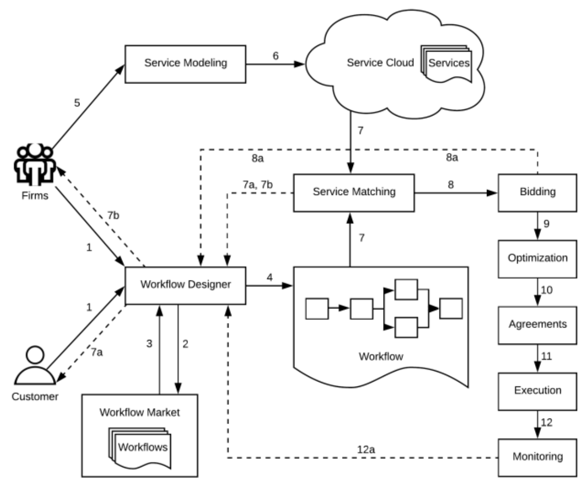

Fig. 1. Process diagram for the proposed architecture

The corresponding numbers in Figure 1 are as follows:

1. Customer designs and initiates workflows through *Workflow Designer*. Workflows are production processes that are defined as repeatable patterns. Firms can also design or initiate a workflow to find

subcontractors for a production process, or to publish ready-made workflows (according to their own or collaborating firms' capabilities) to *Workflow Market*.

2. Workflows can be published to *Workflow Market*. They can be public, private, or hybrid workflows.
3. While designing a workflow, ready-made workflows can be used from *Workflow Market*. These workflows can be used as a base of a design, or used as an element in a design.
4. Workflows are generated by *Workflow Designer*. *Workflow Designer* also acts like an IDE. Workflows are developed, executed, and monitored through this interface.
5. Firms declare their capabilities as services through *Service Modeling*. Example capabilities are as follows: 3D printing, logistics, and testing.
6. Services declared by firms are collected in *Service Cloud*. *Service Cloud* serves as a directory that can be queried for requested tasks. When necessary, simple services can be aggregated to form composite services in the *Service Cloud*.
7. Tasks in the workflows and services are matched. All feasible compositions are taken to the next step.
    a. If no matching services are found for some tasks, approximations are recommended to the customer via *Workflow Designer*.
    b. Alternatively, the firms that have similar capabilities can be queried for new service proposals for the task under consideration.
8. Bids are taken from firms in a predefined time frame.
    a. If no bids are collected for a particular service, customer is notified through *Workflow Designer*.
9. Feasible compositions are evaluated by Optimization. Evaluation criteria is set by customer and include time, quality, reliability, availability, reputation, and cost.
10. Service level agreements are made between customer and firms.
11. Workflow is executed.
12. *Monitoring* for violations in the agreements begin.
    a. Customer is notified for failing tasks through *Workflow Designer*. Matching process can be restarted.

Proposed architecture contributes to services-oriented manufacturing literature as it offers a higher-level workflow based service composition. While it does not feature all Cloud Manufacturing goals, it is much more realizable, and developed primarily for implementation. It adds to workflow based service-oriented approaches [15], [16] utilizing latest developments in IT (particularly cloud computing), removing broker, adding Workflow Market, and accounting for optimization & cost management. It also provides backtracks for Service Matching, Bidding, and Monitoring. In this architecture, Workflow Designer acts like an integrated development environment (IDE) in which firms and customers can design, execute, and monitor workflows. Through this interface, production process is streamlined to user whether the user is a large organization, an SME, or an individual customer.

IV. Impacts in the Next Manufacturing Era

Proposed architecture aims to provide access to centrally organized and shared manufacturing resources. There are economic motivations behind implementing a platform based on this architecture for individual designers, SMEs, large-scale organizations, and policy makers.

Looking from individual designers' point of view, barriers to entry for manufacturing would become lower. Through prototyping, these designers can pursue entrepreneurial opportunities at much lower costs. Prototyping also increases the diversity of products enabling firms to provide personalized products at affordable prices, which is the objective of mass customization. Increasing flexibility encourages innovation and provokes new products, services, and business models, which is one of Industry 4.0 goals [1].

A motivation would be integration of many SMEs to this platform. Their discoverability would increase and they can pull off more market share based on their geographic location, type, quality, pricing, reputation, and so on. On the other hand, large-scale organizations can publish some of their idle capabilities to the platform as services, or they can choose to model some parts of their production as workflows and search for subcontractors. The latter allows an organization to focus on, improve its core competencies, and increase its agility in the marketplace. It can seize new opportunities in the market and adjust its product line to shifting customer demands.

For large-scale organizations and policy makers, it is important to grasp the big picture in the marketplace. For instance, a global organization, which is based in US and subcontracts its production activities in China, can design its production process as a workflow and try to execute it in US. The organization would be able to see what resources and capabilities are missing that makes the same production in US not possible or at significantly higher costs. The organization can choose to focus on building those capabilities. In another example, Government of UK wants to determine the potential impact of Brexit on manufacturing markets. A simulation can be created according to increasing cost of workforce and decreasing offshore production capabilities if some processes were to be designed as workflows in such a platform.

V. Conclusion and Future Work

Theorizing a platform based on the proposed architecture, not every manufacturing organization would immediately become a customer, and not every producer, supplier, or logistics firm would immediately publish its capabilities. Rather, we believe designers, producers, and suppliers that operate at micro scale would be the first users of this platform. Organizations can publish part of their resources and capabilities, or they can choose to model part of their production processes as workflows to find subcontractors. As new transformations including Industry 4.0, Industrial Internet of Things, additive manufacturing, and black factory shape manufacturing, newly formed entities would be interested to become customers or service providers in this platform.

Proposed architecture deals with problems of service-oriented manufacturing at a high level. A prototype implementation is necessary in order to verify this architecture and validate its contributions to manufacturing domain. We are currently working on building a prototype implementation of a platform based on the proposed architecture. As future work, we will continue investigating potential research areas relevant to this architecture including service modeling, service approximation, service suggestion, service matching, and optimization.

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