Towards a Methodology and Instrumentation Toolset for Cloud Manufacturing

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***Abstract*—Cloud Manufacturing is a recent concept to realize real-world manufacturing processes by applying a combination of well-known principles from the fields of Cloud Computing, Business Process Management (BPM), and Internet of Things (IoT) to the manufacturing domain. Cloud Manufacturing assumes using crowdsourcing and outsourcing types of business mobilization to transform local production-oriented manufacturing into global service-oriented manufacturing networks.**

While there have been a number of conceptual frameworks for Cloud Manufacturing, there is still a lack of concrete methodologies and instrumentation. Especially, the integration of generic Cyber-Physical Systems (CPS) shop floors and the support of manufacturing business processes in the Cloud have not been given full consideration yet. Within this paper, we intend to define a research agenda and according missing methodologies and instrumentation to ground a platform for Cloud Manufacturing.

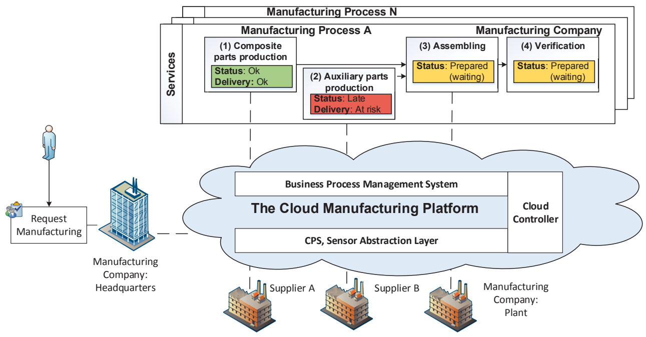

Fig. 1. High-Level Cloud Manufacturing Scenario

I. Introduction

Cloud Manufacturing is a recent concept of networked manufacturing based on the principles of Cloud Computing, BPM, and IoT [1]. The basic idea of Cloud Manufacturing is the integration of single, distributed steps of manufacturing processes as if the complete manufacturing was carried out on the same shop floor [2].

As an example process, we consider the manufacturing of a generic product, which is assembled by a Manufacturing Company in four steps. This is depicted in Figure 1: (1) production of the composite parts by Supplier A, (2) production of the auxiliary parts by Supplier B, (3) assembling the product on the shop floor of the Manufacturing Company's own plant, and (4) verification of the required parameters of the finished product. These single operations can be wrapped into software services. The process model of the this manufacturing process can be created by means of Business Process Model Notation (BPMN) by adding those services as process steps into the model.

Cloud Manufacturing is aimed at the achievement of a minimax effect: minimization of the product life-cycle expenses of the manufacturers and maximization of the production efficiency providing an agile accommodation of the available manufacturing assets to volatile customer demands [2], [3]. Manufacturers are distributed worldwide, yet they may offer similar operations. Therefore, Cloud Manufacturing assumes that manufacturers use crowdsourcing and outsourcing models for manufacturing processes, i.e., by combining services offered by various manufacturers into process models.

One particular reason for the adoption of the Cloud Manufacturing principle by manufacturers is the need for flexible scaling of manufacturing assets [4] and for innovative business technology solutions on a pay-as-you-go basis [5].

As the name implies, Cloud Manufacturing is based on the Cloud Computing paradigm that facilitates the leasing and releasing of on-demand computational resources with pre-installed software, e.g., services, to be used by means of Clouds. One particular prerequisite is the mapping of real-world manufacturing processes to IT systems in order to be able to execute, adapt, and monitor these processes [2].

However, Cloud Computing is hardly seen in the BPM area today [6]. BPM System (BPMS) frameworks are now capable of supporting a fixed amount of resources for manufacturing (business) process execution. The challenge is to supply BPMS by instruments that allow runtime adjustment of infrastructural components to flexibly react on the computational, Quality of Service (QoS), and cost demands while enacting manufacturing processes.

In terms of IoT, Cloud Manufacturing considers sensors, sensor networks, equipment and auxiliary parts, i.e., CPS objects and CPS shop floors in general. The emergence of IoT-based frameworks on top of those manufacturing assets acts as a catalyst for the next industrial revolution, i.e., Industry 4.0, as such frameworks offer methodologies and means to collaborative manufacturing. The services built upon those IoT-based frameworks establish the ground manufacturing service layer to be used in corresponding manufacturing process models during the design time, and in process instances at runtime. An integration of manufacturing services is possible via the

Cloud Manufacturing Platform depicted in Fig. 1, where these services are presented, advertized, leased, and sold as a part of the manufacturing processes maintained in the platform [2].

While a lot of conceptual work has been done on Cloud Manufacturing frameworks and single aspects thereof, there is still lack of concrete methodologies and instrumentation. Therefore, this paper considers research questions, corresponding methodologies, instrumentation, and current efforts to ground the concept of Cloud Manufacturing. The contributions of this work are: (1) The state-of-the art in the field of Cloud Manufacturing is reviewed from three points of view: Cloud Computing, BPM, and IoT (Section II); (2) the research challenges and open questions are formulated and according methodologies and instrumentation are described (Section III); (3) last but not least, an outlook on concrete next steps is given (Section IV).

II. Related Work

In order to get an overview about the state-of-the-art in the field of Cloud Manufacturing, the related work was investigated from the following points of view: Cloud Computing (Section II-A), BPM (Section II-B), and IoT (Section II-C).

A. Cloud Computing and Cloud Manufacturing

Cloud Computing has recently become a mainstream topic in the manufacturing domain [7]. Porting the principles of Cloud Computing onto the manufacturing domain transforms the business model of manufacturing. The work of Xu et al. [7] provides an overview of the research contributions to the concept of Cloud Manufacturing. The promising research area mentioned in their work is the establishment of the Virtual Service Layer for service-oriented manufacturing environments. Further, the authors underline the necessity of achieving plug-and-play capabilities of the CPS objects to ensure Software-as-a-Service (SaaS) as a configuration integration environment. Separately, the emphasis is placed upon the appearance of lots of "embrionic" cloud manufacturing systems, which differ in approaches, combination of used technologies, and implementation, however those embrionic systems tend to perform transformations of conventional manufacturing applications towards Cloud Manufacturing.

Schulte et al. [2] consider the necessity of establishing decentralized manufacturing by means of shared manufacturing assets. The scenario discussed in their work provides an overview of a consortium-based manufacturing style. Manufacturing services are treated in the same way as software services are treated in the Cloud, i.e., explicitly applying the three basic principles of Cloud Computing: on-demand service and resource provisioning, rapid elasticity, and pay-per-use.

B. BPM and Cloud Manufacturing

During the enactment of manufacturing processes in a Cloud Manufacturing Platform, the usage of Cloud-based computational resources allows for the runtime adjustment of infrastructural components based on the actual resource demand. Such flexible business processes enacted on the basis of smart leasing and releasing of computational resources are called *elastic processes* [8]. This allows to support very large and volatile manufacturing process landscapes, which may span different organizations [2]. The research work on elastic processes is a major research challenge on the intersection of BPM and Cloud Manufacturing [6], [9].

In order to gain the feature of elasticity of manufacturing processes, the methodology and instrumentation to manage a manufacturing business process lifecycle in the Cloud are needed [10], [11]. It is equally important to control Cloud computational resources appropriately: to lease resources on-demand, to deploy process steps (single services) onto those resources, to invoke service instances using a schedule, and to release resources after process steps are finished. For real-world manufacturing process landscapes, a BPMS for elastic processes, also known as *elastic BPMS* (eBPMS), has to be able to decide on the appropriate schedule and resource allocation plan in very short time and under potentially heavy load. This kind of decision making, i.e., reasoning upon scheduling and resource allocation, belongs to the NP-hard optimization problems, and existing exact methods can only provide a solution for small-scale scenarios [10], [11], [12], [13]. Applying exact methods on large-scale manufacturing process landscapes is time-consuming or cannot handle the model to provide any solution. Therefore, an elastic manufacturing process enactment requires reasoning methodologies based on heuristic algorithms.

C. IoT and Cloud Manufacturing

According to Wu et al. [4] the problems on the intersection of IoT and Cloud Manufacturing are caused by different levels of heterogeneity of manufacturing resources: multi-domain (sharing of cooperative resources), multi-level (managing all the aspects of manufacturing environment, e.g., design, engineering, manufacturing, and marketing), and multi-granularity (describing the capabilities of CPS objects). There are no fundamental standards that combine volatile functionalities and structure of CPS objects to ensure interoperability, and there is also a necessity to design sensor networks to support manufacturing process monitoring.

Tao et al. [14] propose to summarize Cloud Manufacturing using three levels of applications in the IoT: (1) the interconnection between machines (CPS data identification, access and control), (2) within a manufacturing enterprise (product-oriented data, supply chains, local services), and (3) between enterprises (manufacturing networking, manufacturing service management). Manufacturing-as-a-service is considered to be a core thought in Cloud Manufacturing, and it triggers the transformation from resource- and order-orientation towards service- and requirements-orientation [15]. Having that in mind, the authors discuss the lack of established standards to perform holistic manufacturing asset specification and integration considering different bottlenecks, e.g., digitalization and interconnection of manufacturing assets, virtualization and servitization of manufacturing resources and manufacturing capabilities, and intelligent collaboration between the manufacturers.

III. Methodology and Research Agenda

In the following, we identify open research questions which, in our opinion, are of primary interest in order to realize real-world Cloud Manufacturing. These topics define our concrete future work.

CPS shop floor interoperability is needed to virtualize and to integrate manufacturing assets, to automate the communication between CPS, to promote interoperability, and to establish architectural standards. The corresponding research question can be formulated as "What are the methodologies and instrumentation to provide interoperability of CPS shop floors?" Most important trends are intra- and inter-manufacturing communication with the characteristics of flexibility, scalability, and autonomy focusing on the transformation from the concept of automation towards integrated artificial intelligence [1], [16].

Abstraction and virtualization of manufacturing assets is needed to perform a transformation of the raw stream of CPS data to the virtualized manufacturing assets, to create unified data harmonization services, and to perform holistic service description. The research question to be answered here is: "What are the manufacturing resources and capability patterns to provide mapping onto the process models?" The issue at hand here is the perception and acquisition of manufacturing assets [14], [15], and provision of the virtual models in the Cloud representing the as-is physical configuration of manufacturing and logistic assets. The functionality includes virtual accessing of the manufacturing assets, fault and fail-over handling, and virtualized manufacturing assets monitoring [17].

Service composition is needed to combine manufacturing assets, to consider the multiple-manufacturing case, and to perform the applicable optimization. The corresponding research question can be formulated as "How to create process models, and how can design time and runtime optimization be provided?" As far as service composition is concerned, process modeling is a related topic: The rich knowledge-based models of the virtualized manufacturing assets, the ontologies for the collaboration between manufacturers and for the modeling the supply chains need to be considered here [18]. Aggregation rules and algorithms for manufacturing resource servitization are to be constructed. The full lifecycle of manufacturing processes should be established, allowing encapsulation, search and invocation of the manufacturing services, optimal resource provision and scheduling [2], [14].

Flexibility and elasticity is needed to adjust to the business and manufacturing needs of the manufacturers and customers. The research question addressed here is: "How to achieve elastic processes, what reasoning mechanisms to use for service scheduling and resource allocation?" The features of flexibility and elasticity imply taking into account the heterogeneity of the manufacturing environment and allowing full integration of the manufacturing services into the business processes and providing elastic processes with regard to QoS metrics. The bridging of information in man-to-machine, machine-to-machine and man-to-man manner should be investigated and conforming constraints should be defined [2], [12].

A Cloud Manufacturing Platform is needed to establish manufacturing collaboration, to perform knowledge sharing, to facilitate stakeholder interaction, to virtualize manufacturing assets and manufacturing services, to establish interoperable approaches for intra- and inter-manufacturing communication, and to allow for effective manufacturing process enactment and optimization. These problems have to be addressed by an intermediary middleware delivered by the Cloud Manufacturing Platform [19], [20]. The according research question is: "What are the needed methodologies and instruments to establish the Cloud Manufacturing Platform, and how can we implement them?"

IV. Scheduling and Resource Allocation

Our current research deals with achieving elasticity in the enactment of manufacturing processes. We assume that manufacturing processes are composed from process steps, which are single software services of corresponding manufacturing services instantiated and running on Virtual Machines (VMs) in the Cloud. To enact elastic processes, an eBPMS system with features to control the Cloud is needed (see Fig. 2). Allowing for QoS metrics, the eBPMS makes a schedule for service invocations, provides a plan for resource allocation, and then enacts them.

When a manufacturing process model is foreseen for enactment, a manufacturing process instance is instantiated. When a process step must be enacted, a corresponding service is deployed onto a VM and can then be invoked. Services are assumed to be of several types depending on the CPU load and on the time needed to enact them. Each VM can have only one type of service instance, but simultaneously each VM can have several service invocations. The amount of service invocations depends on the amount of available computational resources, e.g., CPU and RAM.

In our previous work [12], we defined a system model for elastic processes. Based on this, we proposed an optimization problem for the cost-efficient enactment in elastic process landscapes. The optimization problem was modeled as a Mixed Integer Linear Programming (MILP) problem and solved by means of an exact algorithm provided by IBM CPLEX solver. However, that approach was only able to handle relatively small process landscapes, since the used solver was not able to handle large numbers of process instances. This is not surprising, since optimization of elastic process landscapes resembles the service composition problem and is therefore NP-hard [13]. However, process landscapes can become very large, easily comprising thousands of process models [21], [22] and even more process instances. Therefore, our current work is concentrated on substantial extensions of our work by introducing a heuristic algorithm. More precisely, we are working on a genetic algorithm, which can be used in an eBPMS for the computation of a process schedule and the

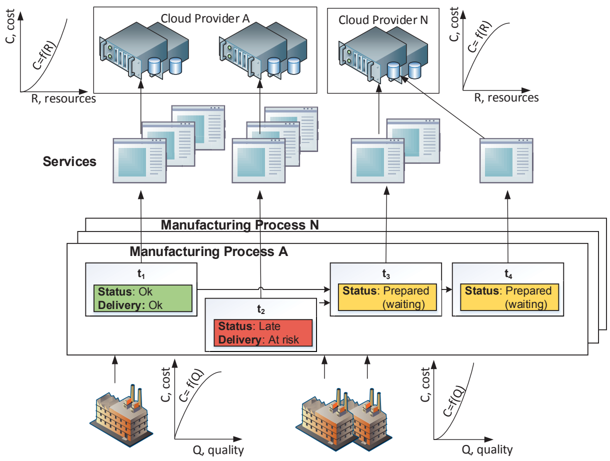

Fig. 2. Scheduling and Resource Allocation Mechanism

necessary resource allocation. Afterwards, we plan to extensively evaluate the performance of our heuristic, comparing it with the existing MILP-based optimization.

While this is a sufficient solution for the technical representation of manufacturing processes in the Cloud, we are also working on integrating the software side with the real-world manufacturing processes. For this, the research questions as defined in Section III are taken into account.

V. Conclusion

Cloud Manufacturing is a recent concept that is intended to facilitate collaboration of machine and human components within the manufacturing industry. A basis in methodology and instrumentation for Cloud Manufacturing is needed to provide CPS shop floor interoperability, to perform abstraction and virtualization of the manufacturing assets, to assure service composition and elasticity in process enactment, and to establish a Cloud Manufacturing Platform. The insights into these methodologies and instrumentation were given in this work. The first major results are expected in the field of scheduling and resource allocation of virtualized manufacturing services in the Cloud.

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