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Intelligent production planning and control in the cloud – towards a scalable software architecture

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Abstract

Today's manufacturing companies are undergoing a transformation towards increased digitalization, automation of manufacturing processes and as well new forms of manufacturing organization and business models. While large-size manufacturing companies are able to follow the pace of such technological developments, small- to mid-size manufacturing companies (SME) often experience substantial problems in adopting technologically and organizationally far reaching concepts as for example propagated by Industry 4.0. In this paper we will discuss a particular problem area of SME – production planning and control – in the light of future manufacturing scenarios. We will outline typical requirements regarding production planning and control in small- to mid-size companies and will propose a scalable cloud-based architectural concept for an intelligent production planning and control (iPPC) software service that we are currently developing as a research prototype and demonstrator solution for industry.

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Keywords:

1. Introduction

Today's manufacturing companies are undergoing a transformation towards increased digitalization, automation of manufacturing processes and as well new forms of manufacturing organization and business models. These developments are driven by recent technological developments and visionary concepts such as the Industrial Internet, Internet of Things, Big Data, Smart Manufacturing and politico-economically motivated programs such as The Fourth Industrial Revolution (aka Industry 4.0).

While large-size manufacturing companies are able to follow the pace of such technological developments, small- to mid-size manufacturing companies (SMEs) often experience substantial problems in adopting technologically and organizationally far reaching concepts as for example propagated by Industry 4.0.

Small and medium-sized enterprises (SMEs) account for over 95% of firms and 60%-70% of employment. They create a large share of new jobs in OECD economies. New technologies and globalization decrease the importance of economies of scale in many activities. Therefore, smaller firms potentially will have the chance to increase their overall contribution in the value chain. However, SMEs have specific strengths and weaknesses. Typical problems faced by SMEs are lack of financing, difficulties in exploiting technology, constrained managerial capabilities, low productivity, regulatory burdens. These problems become even more acute in a globalized, technology-driven environment. [1]

One promising approach that is also being addressed on a political level is the fostering of small-firm networks and clusters. As part of dynamically forming networks of production SMEs can potentially be more flexible and responsive to customer needs than large firms. Such networks can pool resources and share the costs of training, research and development, maintenance and as well planning and control [2].

Cloud-based manufacturing is a new paradigm that builds upon the concepts of service-orientation and virtualization of software resources and underlying hardware [3]. It is not only

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a technological concept that offers ubiquitous accessibility of data and applications but is also an economic opportunity for small- to mid-size manufacturing companies to participate in and benefit from recent technological advancements. Cloud-based manufacturing is expected to enable flexible production network formation to meet an increasing variance in customer demands within reasonable delivery time and low capital tie up [4].

In this paper we will discuss a particular problem area of small to mid-size manufacturing companies – production planning and control – in the light of smart and network manufacturing of the future. We will outline typical requirements regarding production planning and control in small- to mid-size companies and will propose a scalable cloud-based architectural concept for an intelligent production planning and control (iPPC) software service that we are currently developing as a research prototype and demonstrator solution for industry.

2. Challenges and requirements for SMEs

2.1. Challenges

According to the classification scheme of the European Union (EU) Small- and Medium-sized Enterprises (SMEs) employ not more than 250 people and do not have a turnover of more than 50 million Euro. In fact, 99.8 % of European firms (non-financial) fall into this class. However, a closer look into recent statistics reveal that 92.7% of firms are actually micro firms with not more than 10 persons employed. SMEs account for 67% of EU's employment and 58% of value added [5].

In the manufacturing sector 20 % of all enterprises are SMEs. They account for 59% of the employment in this sector and 44 % of the value added. About 80% of the value added is contributed by small and medium sized companies with more than 20 and less than 250 employees. The sectors where small and medium enterprises create almost half of the value added are machinery and equipment, fabricated metal products and food. Other important sectors for SMEs are rubber and plastics, chemicals and electrical equipment [5].

SMEs have a large share in overall economic performance of the EU and as well all other world regions. However, SMEs are also the first-in-row to experience economic turbulences. In fact, SMEs disproportionately negatively contributed to employment decline during years 2008 to 2013 but also contributed disproportionately to the subsequent recovery in 2014. Among the most pressing problems that SMEs experience in recent years are an increasing competition, lack of financial resources, shortage of qualified staff and regulation. Production costs are a problem that SMEs face ever since due to a relatively (in comparison to large firms) high share of human labor in manufacturing processes [5, p. 12].

The latter problem of high labor intensity refers to the larger problem area of efficiency management in SME production processes – a problem area that has been recently investigated for example by Matt and Rauch [6]. Accordingly, SMEs are either not aware of the benefits of lean management or do not have the knowledge to implement respective management concepts. In addition to the knowledge gap lack of financial resources is found to restrain SMEs from investments in advanced production planning and control systems which potentially can increase overall efficiency [7].

A problem area attracting increasing attention from EU policy makers is the fact that SMEs are somehow reluctant to cooperation and networking. Several studies (see e.g. [1], [2], [8], [9]) have shown that SMEs with a strong network of business partners and more specifically innovation partners are more likely to succeed in the long term than those that do not. A main obstacle for cooperation and networking are again the limited resources SMEs own, to initiate and sustain a cooperative venture [2, p. 16]. Despite the reluctance to initiate and maintain cooperation SMEs are usually strongly embedded in a supply chain network which is especially true for the machinery and equipment manufacturing sector. The competency, responsibility and costs of managing such a network is then left over to the hands of large firms, e.g. in the automotive sector, with the price of a strong dependency on the focal firm.

For a subsequent outline of meta-requirements for production planning and control we want to stay with this twofold view – individual and network view – on SMEs.

2.2. Meta-requirements

For an analysis of meta-requirements, we use a typical PPC process as a reference framework. Typical activities in PPC can be divided into long- range and short- range planning activities and ongoing control activities.

2.2.1. Long-range Planning

Long-range planning goes in hand with the overall business planning activities of a manufacturing company. A company's business vision and derived long-term objectives are the reference point for long-range planning. The outcomes of long-range planning are rough-cut production programs that indicate the product families, the quantities to be manufactured and the human and technical resources needed.

In practice SMEs rarely have explicit strategies regarding their business future [10]. Rather SMEs aim at staying highly responsive to market needs. Therefore, Make-To-Order (MTO) and Engineer-To-Order (ETO) principles are increasingly applied among SMEs [11]. However, also for MTO and ETO manufacturing resources have to be planned in advance.

Long-range planning therefore requires a solid base of a company's historical sales data and its linking with future-oriented data such as market developments and technological trends. Data sources need to be exploited (e.g. social media data) to anticipate the future development of product offerings and the required machinery. For SMEs within a supply chain network these data can potentially be collected from the focal firm or other downstream partners in the supply chain.

Long-range planning for production networks requires a central planning unit that collects and maintains data from the involved network partners to be able to learn for future decisions regarding optimal network configurations [12].

Depending on the actual nature of a network – closely versus loosely coupled – planning results range from strategic decisions regarding partner selection and investments to mere production forecasts.

2.2.2. Short-range Planning

While long-range planning is usually performed on a yearly or more basis short-range planning is performed on a monthly and/or weekly basis. Short-range planning is ideally based on long-range plans and takes into account the actual order situation and the actual state of the production process. The outcome of a typical short-range planning activity is a consolidated schedule for the next production period taking into account new order priorities and shop floor disturbances, e.g. maintenance plans and staff absences. In addition, requirements regarding additional staff, shifts, machine adaptions are formulated.

For SMEs short-range planning is crucial as actual resource capacities need to be evaluated against the order situation and requested delivery dates [13]. In many cases small enterprises have substantial problems to reliably evaluate their actual state of production regarding work load and inventory [14]. One reason for this is that data on inventory and work load often simply does not exist as adequate information systems are not available. In case a respective infrastructure exists, data is not always reliable as completion confirmation and inventory is not performed on a regular basis or is performed only on a coarse grained process level. Also data on qualifications and availability of staff, specifications of machines and their potential for flexibility is often missing or imprecise to be able to plan.

Short-range planning requires both transparent and realistic long-range plans and accurate information on the actual and near future state of operations. As a consequence, a short-term planning tool for SMEs must be able to access data sources, e.g. from sales order management. Detailed order data and technical product specifications must be available to be able to group orders, compute lot-sizes and minimize setup times.

Short-range plans are a frame of action for subsequent manufacturing execution. Therefore, short-range plans need to be easily understandable and need to be accessible on the shop floor. Different types of visualizations must be offered according to individual information needs. E.g. costs versus time-line visualization. On the network level short-range planning needs to have access to the actual state of the manufacturing facility to be able to launch appropriate measures, e.g. the acquisition of additional services to increase capacity in the short-term.

2.2.3. Control

Control activities are targeted at closing the gap between short-range plans and actual. Production control takes place in an ongoing manner and can be divided in monitoring, comparing plan against actual and taking action.

Control activities in SMEs are usually based on a combination of principles and technical systems, e.g. CONWIP or Kanban, that determines the rules and tools how orders are routed through production and which conditions must apply for a production process to be under control [7]. In practice, SMEs have only limited knowledge of such control principles and therefore often adhere to simple first-in-first out (FIFO) principles for order release in combination with simple push control, e.g. with printed work plans that accompany a work piece on its way through production. The result is a high rate of delays, high inventory levels and unbalanced human and technical resources [14].

Control activities in SMEs require an approach that allows to implement simple control principles and scale them up to more sophisticated principles as an SME grows both in terms of order frequency and in terms of product variety. A key requirement for SMEs is the possibility to access actual data from the shop floor. Therefore, interfaces must be provided that allow for a rapid vertical integration of planning, control and execution layers. A respective control system needs to be integrateable into a larger network level planning and control system.

3. A cloud-based architecture for intelligent production planning and control as a service

3.1. State-of-the-art in Cloud-based Manufacturing for SME

Cloud manufacturing is a new manufacturing paradigm developed from existing advanced manufacturing models and enterprise information technologies under the support of cloud computing, Internet of Things (IoT), virtualization and service-oriented technologies, Semantic Web and advanced computing technologies [3], [15]. This network manufacturing model exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable production lines which enhance efficiency, reduce product lifecycle costs, and allow for optimal resource allocation in response to variable-demand customer generated tasking, [16], [17], [18]. The major idea of cloud manufacturing is that companies in all sectors of manufacturing will be able to package and expose their production resources and production capabilities in the cloud to transform them into manufacturing services. In recent years many architectural concepts for cloud-based manufacturing systems have been proposed in literature, see for example [19], [20], [21], [22].

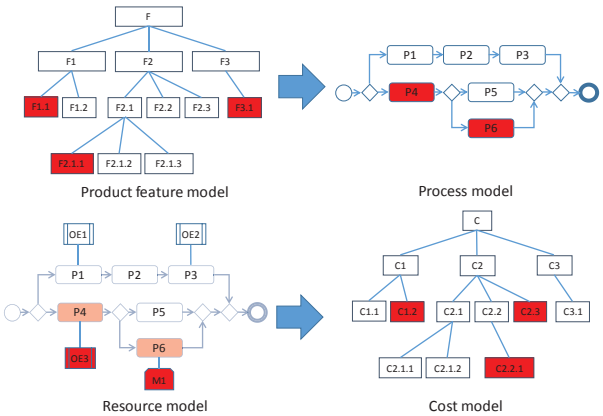

Fig. 1:(Process-)Model-driven approach to Production Planning and Control

However, only little research works, e.g. [19], [23], have addressed the role of production planning and control in future production scenarios. Even less research has been dedicated to production planning and control as a service which is actually a necessary consequence of cloud-based manufacturing.

3.2. Process-driven Production Planning and Control

Process-oriented management approaches in combination with service-oriented architectures have gained increasing interest in both academia and industry. A major advantage of process-oriented design of management and information systems is grounded in the scalability and flexibility of respective systems.

The basic idea of process- oriented (or process aware) information systems (PAIS) [24] is that business logic and software functionality is entirely decoupled. At the heart of this approach lies a process architecture or multi-level process model that formally describes the flow logic of a business process. The process model represents the business logic that is used to fulfil a customer order. It determines the exact order of all activities performed and defines the software services needed. Consequently, PAIS can be flexibly and easily

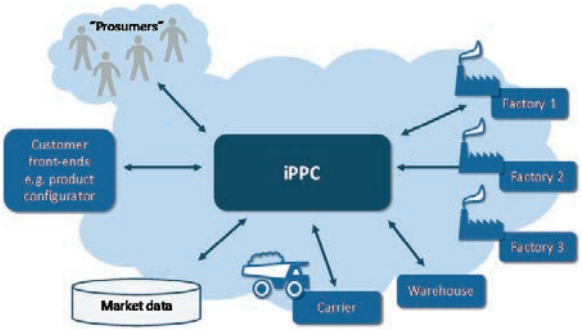

Fig. 3: Intelligent Production Planning and Control Service in the Cloud

configured on the level of the process model rather than having to change the software behind. PAIS are therefore suitable to support fast changing (agile) business processes.

In recent years the theoretical foundation of process aware information systems has reached a rather mature stage [25]. Many large software vendors have already incorporated business process engines together with service-oriented approaches in their products, e.g. SAP, Oracle. Hence, in the domain of manufacturing process management approaches have been implemented only to a very limited extent. In manufacturing companies, processes are usually identified and semi-formally described for the purpose of high-level documentation of production related processes, e.g. planning and control, maintenance, production, or low-level descriptions of work procedures. A systematic and complete formal description of production related processes from high- to low-level (a process architecture) is usually missing.

Our proposed architecture for a cloud-based intelligent production planning and control (iPPC) service is built upon the idea of a process-orientation and service-orientation. For this purpose, we propose a model-driven approach (see figure 1) that allows for the complete and consistent formal description of production related processes. Process models are used to describe the flow of activities together with the material flow and information flow.

For modeling of manufacturing processes, we combine techniques for product feature modeling with process modeling. To be precise, we infer process models (or process model variants) from product feature models. Based on the process model (the activity flow logic), necessary resources are derived and costs and dates can be computed. In other words, we integrate the concept of "bill-of-material" (formally, goes-into-graph) and "work plan" (formally, routing) into a single concept – a process model. The process model is used as the single formal and complete description of a manufacturing process. Process configuration for a particular product configuration are inferred through planning techniques from artificial intelligence as proposed for example in [26].

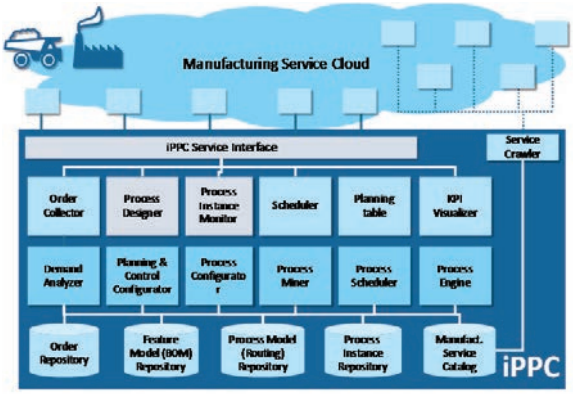

Fig. 2: iPPC Architecture Concept

3.3. Production Planning and Control as a Service

Given a strong ontological foundation for production related processes we are currently developing a service-oriented architecture for production planning and control in the cloud. For this purpose, we largely abstract from the process level and provide an architectural frame-work that fits both the lower level and as well the higher level production planning and control in a network. Thus, scalability regarding the concrete nature of a production scenario (e.g. number of entities involved, product characteristics) is enabled. The main subsystems of our architecture are described in the following sections (see also figures 2, 3).

3.3.1. Demand analyzer / order collector

Especially in SMEs MTO and ETO processes are frequent. The customer order is therefore the central point of reference for determining the optimal fulfillment process. For long-term and short-term planning customer orders are a valuable data source for estimating future demand and making respective decisions for material purchasing and resource allocation.

The Order Collector component collects customer orders and analyzes the structure of demand regarding product

features, customer characteristics, delivery dates and prices. A major feature of this component is the prediction of future demand. For this purpose, also changes in demand structure will be analyzed and predicted as best as possible.

We plan to employ machine learning methods to uncover qualitative and quantitative patterns in the demand structure and advanced statistical methods to predict future customer orders. In addition, also interfaces to external data sources will be implemented, e.g. weather data or price indices.

3.3.2. Process Designer

The Process Designer (PD) is the primary user interface to design/model a production process. As production processes are usually performed by multiple parties also the design phase must allow for participation and collaboration.

The PD is based on a wiki engine that allows for the conceptual modeling of processes and a highly iterative and collaborative development of a process model. The PD supports multiple formal modeling languages and ways of interaction, e.g. through a revisions history and commentary feature. Thus, a consistent version management of process models is possible.

Process model describe a production processes on an abstract level. They do not refer to implementation details, e.g. how the work center is construed, but describe the input/output relations, refer to the involved resources, e.g. work centers, materials, machines, qualifications, on a qualitative and quantitative basis.

Once a process model reaches a mature state it can be deployed as a service or at least connected to a service. Process models then can be instantiated from the evocation of a service or an event.

3.3.3. Process Repository

Each process model created via the PD is stored in a process model repository. The repository also holds all revisions of a process model and as well all the links between process model – the process architecture.

For a given customer order and product, a suitable process model is selected automatically from the process model repository. The process model then serves as the orchestrator for the sequencing and scheduling of production services. Process model instances are the virtual counterpart of “real-world” production processes. All data generated by a production process is related to the process instance. Thus, production data can always be related to a concrete date, time and production order. Process instances and related data are stored in a Process Instance Repository which can be used for statistical analysis of production processes and as well can be used to sup-port real-time production control activities.

3.3.4. Process Engine

The Process Engine (PE) or Process Controller is the core component of the whole Process Management System (PMS). Together with the Process Designer and the Process Repository it constitutes the PMS (figure 3). The PE keeps track of process instances and is the primary control/orchestration unit of the whole production process.

The PE is used to enact a process model for a given business case. In the context of production, a case is usually a customer order or production order. Manufacturing companies handle multiple production orders and related process instances at the same time. The PE keeps track of overall process (order) state and also keeps track of all sub-processes’ states. Thus, a fine-grained progress monitoring and production control can be achieved.

3.3.4.1. Process instances are closely connected to some kind of event processing. Therefore, the process engine has as well an event processor component that is able to relate data streams stemming from the process or external sources to event definitions which in turn trigger a certain process logic. On the lowest level an event processor takes sensor data as input for subsequent event processing.

3.3.5. Scheduler

When production orders are released to production, detailed scheduling of the related process variant and sub-tasks will take place. Determining realistic start and end dates for a production order based on the actual situation on the shop floor is a challenging task which requires adequate algorithms and computational resources. By adequate we mean that there is no such thing as the best solution for all scheduling problems.

Rather, we aim at offering domain specific scheduling techniques that are automatically configured to fit a production service provider’s domain and company specific needs. In addition, scheduling will be knowledge-based which means that scheduling will make use of a memory component that provides the actual state of the production and remembers past decisions under similar circumstances. For this purpose, the scheduler relies heavily on the process instance repository.

Related with scheduling is also the need to visualize production schedules for human workers. The field of information visualization has advanced the possibilities of classical Gantt charts. In a recent effort, we have studied several visualization techniques such as mosaic charts, 3D-graphs and two-mode graphs.

3.3.6. Service catalog and crawler

The process architecture determines the logical flow of work, materials and information. Services are the software interfaces to production resources. For an intelligent production planning and control service, knowledge of services that fulfil the processes is crucial. Therefore, we plan to extend state-of-the-art description languages (e.g. WSDL or WS-BPEL) with a physical view that includes language elements to describe material input and output together with the information flow. The basis for specifying services (production and logistics) is the process architecture. Processes models on arbitrary levels provide the necessary information (e.g. input/output variables) for the service specification. In order to provide reliable information regarding the delivery dates, the availability of resources and the costs, data on the actual performance of such services (internal or external) will be stored and analyzed to support

future decisions regarding service partner selection and network optimization. All internal service specification will be made accessible for external parties through a *Service Catalog*.

The *Service Crawler* component is an autonomous component that regularly browses external services catalogs for production service offerings and grabs the specifications to be used in future planning and control decisions. An internal *Service Cache* will store a subset of service specifications that has been used previously together with operational data, such as average execution time to allow for evaluation of service reliability and performance.

4. Implementation

We are currently developing a prototypical production planning and control service. For this purpose, we take a greenfield approach, radically rethinking existing software engineering approaches in the field of production planning and control. In particular, we base our software architecture on the principles of process-orientation rather than on object orientation. This approach, makes it possible to flexibly adapt a service to the requirements of the different levels of production planning and control (network, organization, factors, work center, machine).

The technology stack we use is based on light-weight frameworks from the domain of web application development. For the Process Designer component, we make use of a previously developed framework for graph-based modeling. This approach has been proven to facilitate participation of non-expert software engineers, e.g. students of industrial engineering. Moreover, installation requirements and operation requirements are extremely low which is important for the SME sector. Although the prototype is meant to be independent of particular domains, we will use the TU Wien Industry 4.0 Pilot Factory as a practical use-case and test bed.

5. Conclusion

In this paper we proposed a conceptual architecture for an intelligent production planning and control service (iPPC) in the cloud. The service is intended to be scalable in the sense that it can be used independent of the size of a company, the level of planning and control (work center to network level) and the complexity of the demand structure. The basis for scalability is a process-oriented/model-driven approach that replaces the traditional object-oriented approach to production planning and control. Scalability and availability of production planning and control services is crucial for SMEs willing to adopt advanced planning and control techniques. Given that a critical mass of SMEs uses iPPC also planning and control on the network level is feasible as reliable data will be generated that is a prerequisite for network level configuration of manufacturing services.

The proposed architecture reflects the principal idea and structure of iPPC. Currently, we are in the final stage for developing the main components such as the Process Designer, the Process Engine and Scheduler.

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