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# Simulation based Validation of Supply Chain Effects through ICT enabled Real-Time-Capability in ETO Production Planning

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## Abstract

According to Industry 4.0, real-time information in production planning and control, shows a high potential for optimizing the whole supply chain. The paper considers the plant building industry, especially the off-site fabrication and on-site installation. Traditionally, production planning is centralized following a Master Schedule that rarely is up to date, ignoring deviations on-site. As a result, components are delivered in advance or too late, which create non-value adding activities and high inventory levels. The paper proposes an ICT-supported nearly real-time capable production planning approach, which by means of a simulation, shows a drastically reduction of the inventory level on-site.

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*Keywords:* Real-Time Capability, Production Planning, Digital Factory, Engineer-to-Order, Just-in-Time, Supply Chain Management, Industry 4.0

## 1. Introduction

With the introduction and development of ERP (Enterprise Resource Planning) systems, the foundation was laid for centrally managing data creating a common database for production companies. Advanced Planning and Scheduling (APS) systems develop solutions for complex planning and scheduling problems using optimization

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algorithms [1]. By intelligent and automated planning and control systems, future smart factories are able to provide real-time information throughout the entire supply chain [2]. The increasing trend towards digitalization allows a more accurate and reliable production planning and control through (nearly) real-time data. If information is always available in the entire supply chain and kept up-to-date at all times, a future demand driven value chain and factory becomes an achievable goal. In symbiosis with highly responsive, reconfigurable and time efficient production systems [2, 3] emerging trends towards mass customization [4, 5] can be managed. With the implementation of Cyber-Physical Systems (CPS) and Internet of Things (IoT) sensing enterprises become reality. Manufacturers can sense deviations from the production plan as soon as they appear and identify delays in the logistics network in real-time [7]. A central issue in the digital, sensing and smart factory of the future remains, how digital integration and real-time data monitoring can be realized in practice [6].

The plant building and construction industry is characterized by an off-site fabrication and on-site installation of components. Traditionally, fabrication is based according to a static Master Schedule, which rarely considers deviations on-site. As a result, components are delivered too early or too late to the site for installation, causing the following kinds of waste: 1) The overfilling of buffers on-site, inducing handling and searching activities and increasing the risk of damages. 2) Construction interruptions due to missing components causing waiting times and low productivity levels on-site.

The paper is structured as follows: First, new challenges and opportunities for production planning and control through the emerging trend of Industry 4.0 are described. In a short literature review, the actual state of the art in real-time capability in production planning and control is summarized. Next, the concept of a (nearly) real-time production planning approach for the ETO plant building and construction industry is presented. In this context, due to usually long lead times, real time has actually a slightly different meaning as in industrial series manufacturing. Thus, the exchange of management information is based on a weekly frequency but a true real time availability of management information (e.g. minutes or seconds) would be nonsense. Afterwards, the effects of the proposed approach will be validated through a simulation using the tool FlexSim.

## 2. Real-time capable production planning and control in the digital factory of the future – state of the art

### *2.1. Industry 4.0 – challenge and opportunity for production planning and control*

After mechanization, electrification, and computerization of industrial production we are now in the Internet of Things (IoT) era or also called as the fourth industrial revolution (Industry 4.0). With the emerging trend of Industry 4.0, companies will connect and link their products, machines, storage/handling/transport systems, and other resources worldwide as CPS in the so-called ‘smart factories’ [8]. The term “Industry 4.0” is actually highly discussed as a vision in research and industry to revolutionize production management and the factory of the future. We are now at the beginning of a new epoch in production, where web technology and intelligent automation as well as digitalization support the development of CPS [9]. The concept of Industry 4.0 is strongly related to the term CPS [10]. The term emerged around 2006, coined by Helen Gill at the National Science Foundation in the United States [11]. CPS capture data of the real world via sensors, process them with software from embedded controllers, use the Internet and cloud computing for mutual communication between the connectors, and interact with real world by means of mechatronic actuators [12]. The desired benefits are evident: intelligent, networked objects and autonomous control systems are able to reflect customer demands in real-time [13].

Advances in production planning and control have focused on increasing the sophistication of the planning function [14]. CPS act as provider to change the principles in production planning, from centralized production concepts to decentralized manufacturing systems [15]. Many manufacturing companies are still at the very beginning of collecting and using data gathered during production processes, dealing with the problem that major parts of the collected data are outdated or biased and far away from real-time. Emerging Industry 4.0 technologies in data gathering of production management offer the opportunity to receive accurate information and precise feedback for a reliable production planning and control [16]. Production planning and control (PPC) should be able to provide feedback about disturbances directly when they occur and communicate this feedback to the factory-level PPC systems [14]. Therefore, information of all involved products, processes and resources are needed in real-time. However, stakeholders within production management had rarely access to this real-time information [17].

### *2.2. Real-time capability in production planning and control*

There is still lack of information available in the shop floor. Usually, an ERP system alone lacks the functionality to offer detailed visibility into the manufacturing workflow and information on individual critical resources. As practical examples, WIP levels and the location of products in the production processes could be very helpful in order to support intelligent and dynamic decision making as unexpected events occur. Since synchronization of existing ICT-systems (like ERP, APS, MES, etc.) lacks, it is crucially important to develop solutions before the seamless integration of such a real-time planning and control system can be employed [2].

Different authors have developed approaches for real-time capable production planning and control. Schuh et al. [18] introduces very early the need for High Resolution Production Management and describes an approach to achieve real-time capable production planning and control. Key element of this concept are sensor-actuator networks, which use automatic identification technologies such as RFID, barcode or data matrix to automate status reports to keep employees out of value adding operations [19]. Arica and Powell [2] illustrate a conceptual framework for real-time production planning and control. They also emphasize the application of radio frequency identification as one of the most advanced and promising emerging real-time data capture technology available to manufacturers. Lanza et al. [20] developed an approach based on intelligent rescheduling for production control in global manufacturing networks, which enables an immediate reaction on randomly occurring trouble events using information of CPS. Georgiadis and Michaloudis [21] elaborated a comprehensive real-time PPC system for arbitrary capacitated job-shop manufacturing adopting a system dynamics approach proved to be appropriate for studying the dynamic behavior of complex manufacturing systems. Shop performance in terms of average backlogged orders, work in process inventories and tardy jobs could be improved.

## 3. Proposed methodology and approach for Engineer-to-Order plant building industry

### *3.1. Centralized Production Planning and Control (status quo)*

Generally, first tier ETO suppliers in the plant building and construction industry consist of three core phases: Engineering, Fabrication and Installation. A special characteristic is that important components are engineered, fabricated and installed on-site according to a specific customer order [22, 23]. As practical examples, companies that produce steam turbines for power plants or façade supplier companies in the construction industry could be mentioned.

Usually, Material Requirement Planning (MRP) is performed centrally within the ERP-system of the first tier supplier [24]. As a result, ETO-components are fabricated and delivered to the site for installation according to a static Master Schedule and not according to the real demand. Static means in this case that the schedule is not frequently updated and therefore it does not reflect deviations throughout the supply chain. In Fig. 1, the schematic depiction of a traditionally first-tier ETO supply chain in the plant building and construction industry is visualized. Usually, one fabrication shop has to supply ETO-components to different installation sites. In this case, as an abstracted example, the first-tier supplier delivers to four different installation sites. The Engineering department elaborates the approval design to be presented to the customer for the final release. According to the approval design, shop floor drawings and Bill of Materials (BOMs) are elaborated, which specify the different components, their material and so on [22]. Based on shop floor drawings and BOMs, the needed ETO-components are fabricated (in- or outsourced) and delivered to the site for installation.

In Lean Manufacturing, the consistent amount of production instructions released at the pacemaker process and simultaneously taking away of an equal amount of finished goods is called ‘paced withdrawal’. This consistent increment of work is called ‘Pitch’ and is calculated by determining how much work can be done at the bottleneck process in one Pitch interval [25]. As a result, this Pitch becomes the basic unit of the production schedule and the common unit for production instruction between different customer orders. In [22] and [26], the pitching concept was applied to a construction supply chain. The Pitch is defined per task and it specifies how much construction progress (e.g. how many rooms) should be completed by a specific crew in a given time period (e.g. day or week) on the installation site. According to this indication the amount of needed components on-site, as well as the needed shop floor drawings are determined. In Fig. 1, the Master Schedule is configured in a weekly granularity level. As a result, in every calendar week (CW), one Pitch is installed at every installation site (1 to 4) and every three CWs an amount of components of three Pitches exits the fabrication shop of the first-tier supplier. The supply chain is coordinated by means of a centrally organized Master Schedule within the ERP-System of the first-tier supplier. Every installation site suffers from uncertainty in activity durations (deviations), where according to [27] an exponential distribution was considered. In [27] researchers collected real world data from two building projects and performed a curve fitting identifying four different probability distributions of some on-site and off-site activities. As a reference, ‘rework on rough-in plumbing on-site’ following an exponential distribution was considered. This reflects best installation works like façade construction on-site. According to an expert interview, uncertainty in activity durations of façade installation on-site reflect an average deviation of 5 days [28]. As a result, these parameters where used to configure the simulation model described in paragraph 4.2.

As visualized in Fig. 1, the traditionally centralized production planning and control suffers from a missing feedback loop between the customer (installation site) and the supplier. More in detail, deviations of the different installation sites are not considered in real-time in the Master Schedule, which leads to the following types of waste: 1) installation interruptions on-site due to missing material, 2) overfilling of buffer zones in the fabrication shop and on the installation site and 3) extension of lead times.

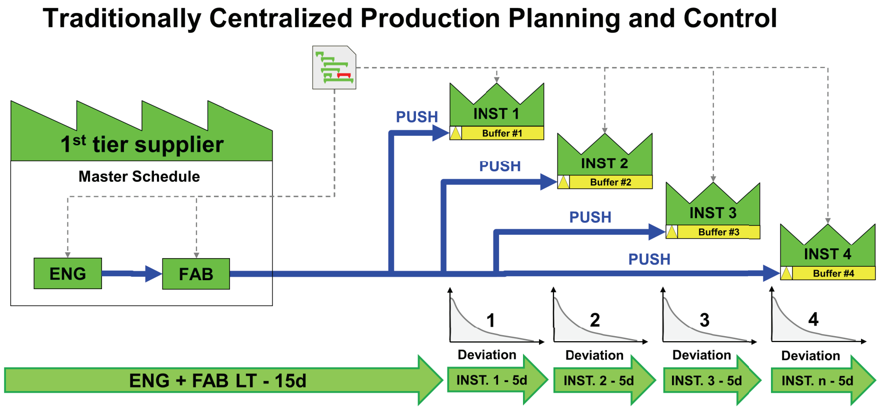

Fig. 1 Traditionally Centralized Production Planning and Control (Push)

### 3.2. Decentralized and Real-Time Production Planning and Control

In Fig. 2, the approach for a decentralized and real-time production planning and control is visualized. As main difference, every installation site requests the needed components three CWs before. This period was chosen according to an expert interview, where experts from installation practice stated that usually, a prediction of the work to be done on-site, of more than 15 days (three CWs) is not possible in a reliable way [28]. As a result, to reach an on-demand fabrication and JIT delivery of components, the delivery time of the fabrication shop should not exceed three CWs. As visualized in Fig. 2, every installation site schedules the tasks to be performed and accordingly the needed material in an autonomous way with a time horizon of three CWs. This is done according to the Cyclically Planning approach [29]. In brief, every week every installation site (foreman) schedules the work to be performed with a preview of three CWs. As practical example, at t=0 the work to be performed in CW 1, CW 2 and CW 3 is scheduled. The needed material in CW 3 is requested at t=0 by means of ‘Release 1’ in Fig. 2. As soon as CW 1 is finished, the performed tasks are recorded and a next planning for CW 2 until CW 4 is done. This process repeats until CW n. Because the Engineering department needs a long preliminary lead-time, it is organized according to the Master Schedule. As different from the traditional approach visualized in Fig. 1, production planning in the fabrication shop is organized according to the order backlog list, which is prioritized in real-time based on different customer requests (Cyclically Planning on the installation sites). More in detail, the prioritization of Pitches (amount of components) to be delivered to the different installation sites is ordered according to the

Master Schedule and according to the indicator *Prio*, which measures the filling degree of the different installation buffers (1).

$$\text{Prio} = \frac{\#\,Pitches\ in\ Buffer}{Buffer\ size} \tag{1}$$

In short time intervals, like every week, the order backlog list is actualized or rather prioritized. The installation site, where products are going to be delivered, is selected based on the originally Master Schedule and according to the installation site with the lowest indicator of Prio. As such, if delays are going to happen on the installation site, the feedback loop prevents an overfilling of buffer zones, or in the worst-case installation interruptions due to missing material. This allows reaching a production on-demand and delivery JIT to different installation sites preventing the following types of waste: overproduction, excess moving and handling, long lead times and costly waiting times on-site.

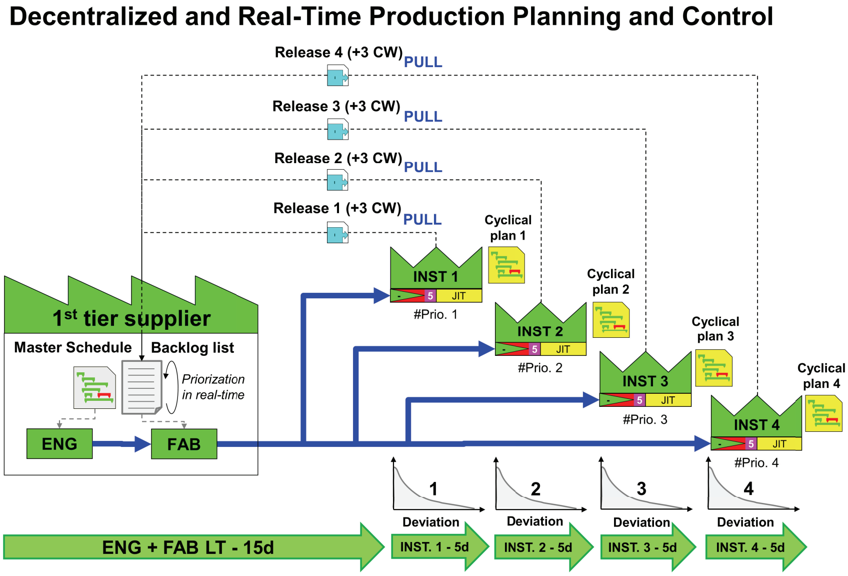

Fig. 2. Decentralized and Real-Time Production Planning and Control (Pull)

## 4. Simulation based validation of the approach

In this part the before explained approach for real-time capability in ETO production planning and control will be examined and validated using the simulation software FlexSim. First, the discrete event simulation software FlexSim is described in a brief overview. Subsequently, the structure of the simulation model is explained and finally the results of the simulation are described.

FlexSim software is a typical integration between virtual reality technology and discrete object-oriented simulation [30]. FlexSim, as commercialized software, is one of the most powerful tools for modeling, analyzing, visualizing in 3D, and optimizing any imaginable process - from manufacturing to supply chains, abstract examples to real world systems, and anything in between [31] [32].

### *4.1. Architecture of the simulation model and definition of simulation parameters*

The process flow chart available in Flexsim is used to design discrete-event models with block diagram schemes. Abstract objects called ‘tokens’ transit between blocks instantaneously, triggering at their arrival states transitions in the model. The blocks are called ‘activities’ and define a transition in the state of the model or a delay in the flow of the token. The architecture of the simulation model in Flexsim, which is based on Fig. 2, is presented in Fig. 3.

The tokens represent two different entities. Firstly, they represent the Pitches, encompassing the components manufactured in the shop floor (factory) and delivered to the site for installation. Secondly, they represent a customer request (of a Pitch), which means an order to produce a new Pitch in the factory chosen from the order-backlog list. The model consists of two main processes: a) The factory model consists of the order backlog, the manufacturing process and an actualization loop, which orders (prioritizes) the backlog by the priority number every week. The backlog is represented by a Flexsim list, which contains the requested Pitches (orders of components) from the different installation sites. The factory lead-time is modeled with a simple queuing node composed of a resource and a delay. The factory lead-time is set to 15 days, where three tokens (Pitches) represent the components for different installation sites and are processed simultaneously. The actualization loop is represented by a sub-process, which chooses the three tokens from the order backlog using the logic exposed in section 4.3. First, it orders the backlog according to the Master Schedule. Then, it orders the backlog using the priority number (Prio). Finally, it takes the tree tokens with the highest priority from the order backlog and releases them to the fabrication shop. This loop runs each three CWs (according to the lead-time of the factory). b) The models of the different installation sites are composed by the installation process and a decentralized and cyclical planning loop (Fig. 2). The installation process is modeled with a queuing node using a resource and a delay of a Flexsim activity. The installation time on-site is subject to stochastic delays, which are simulated by an exponential distribution [27] with a mean delay of 5 days. The cyclically planning of the different installation sites requests tokens (Pitches) to the order-backlog in a weekly frequency with a preview of three CWs.

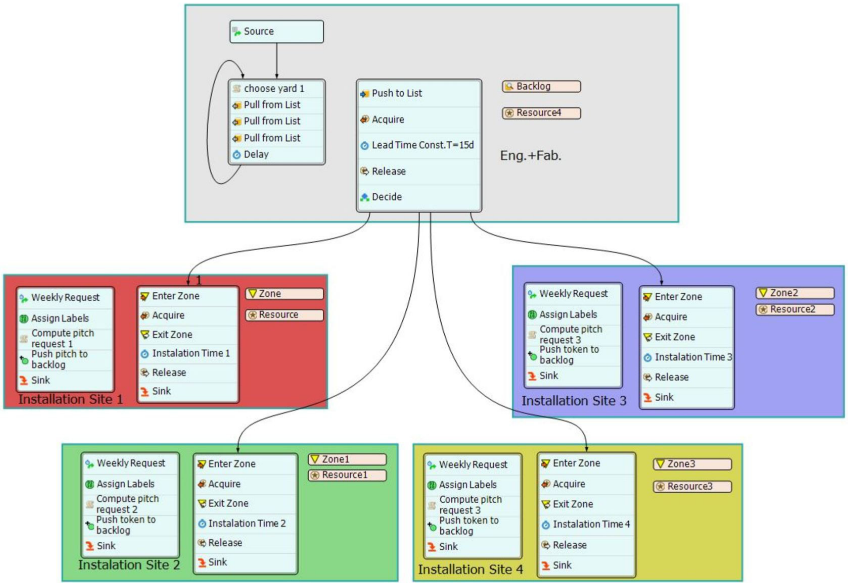

Fig. 3. Simulation model of decentralized and Real-Time PPC (Pull)

### *4.2. Results of the discrete event simulation*

At each run of the simulation, we have collected two main data streams from the model, the current content of tokens in the buffers on the installation sites and the average of this content. In Fig. 4, the average content of the traditional Push model (left) and the proposed Pull model (right) from Fig.3 is visualized. The zones illustrate the different installation sites. In the Push model, the production according to the Master Schedule causes the accumulation of Pitches in the buffers of the installation sites. On the other hand, by introducing a feedback loop from the different installation sites, requesting the Pitches in real-time, a production on-demand can be reached. According to the simulation, the average content of the buffer is reduced in the Pull model by approximately 30%.

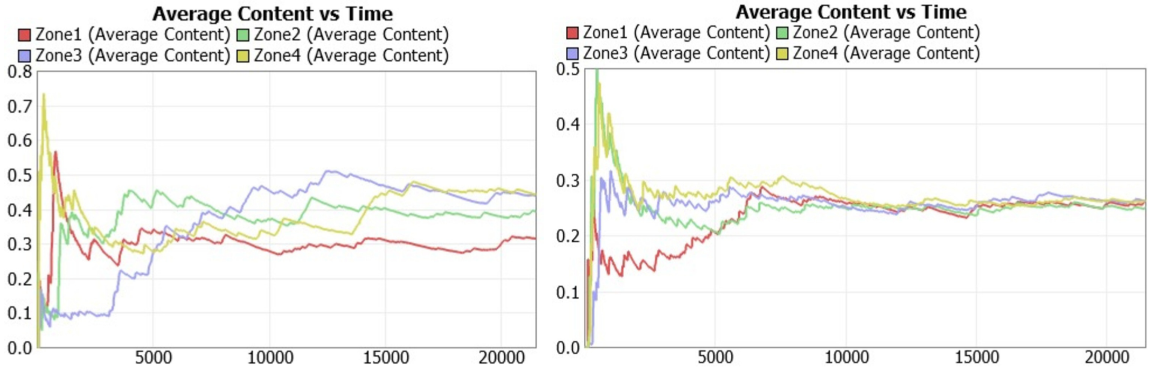

Fig. 4. Simulation results Average Content vs Time (left Push and right Pull)

## 5. Conclusion and Outlook

Traditionally, in ETO-supply chains with a consecutive installation on-site, MRP is performed by the ERP system of the first-tier supplier. The delivery of ETO-components to the site for installation is usually organized according to a static Master Schedule, which does not reflect in real-time deviations of different installation sites. This results in a Push production system with long lead times, high and uncontrolled levels of stock and a high amount of non-value adding activities like searching and waiting.

Industry 4.0 principles, like ‘Real-Time Capability’, ‘Decentralization’ and ‘Self-Control’ are the main enabler to obtain lean, agile and responsive production systems in the ETO-plant building and construction industry. The result of the simulation reveals the potential of real-time control information in ETO-supply chains. In fact, the real-time feedback loop reduced the buffer of each of the four installation sites from the simulation model significantly. As a limitation of the model, the additional positive effect of a production on-demand and JIT delivery on the reduction of installation delays is not considered in this work. Future research will be focused on considering real-world data of two Italian companies working in the field of plant building and construction to validate the probability distributions of task deviations on-site. Moreover, the approach of a decentralized and Real-Time Production Planning and Control will be implemented and validated in several practical case studies from industry.

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