Dallasega, P., Marcher, C., Marengo , E., Rauch , E., Matt , D.T. and Nutt, W. (2016) "A Decentralized and Pull-based Control Loop for On-Demand Delivery in ETO Construction Supply Chains." In: *Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction*, Boston, MA, USA, sect.8 pp. 33–42. Available at: <www.iglc.net>.

A DECENTRALIZED AND PULL-BASED CONTROL LOOP FOR ON-DEMAND DELIVERY IN ETO CONSTRUCTION SUPPLY CHAINS

Patrick Dallasega[1], Carmen Marcher[2], Elisa Marengo[3], Erwin Rauch[4], Dominik T. Matt[5,6], Werner Nutt[7]

ABSTRACT

Engineer-to-Order (ETO) process chain types with a successive installation on-site are common in plant building and the construction industry. Usually, the core processes Engineering, Fabrication and Installation are disconnected, which creates high levels of Work in Progress (WIP) and long lead-times. Furthermore, up to date information about the construction progress, as prerequisite for an on-demand delivery of ETO-components is always difficult to obtain. Usually, to prevent a lack of material on-site, costly intermediate storages are used, which extend the delivery time. Well-known approaches in research, like the Last Planner System (LPS) or the Location Based Management System (LBMS), increase collaboration on-site and improve the reliability of construction schedules, but have a limited impact on synchronizing the supply chain to the construction progress. The approach presented in the paper describes how off-site and on-site production can be coupled, to reach short construction lead-times without wastefully intermediate storages. A first IT-prototype, based on "Industry 4.0" principles, was implemented and tested in an Italian medium-sized ETO construction supplier.

KEYWORDS

Engineer-to-Order, Just-in-Time, Supply Chain Management, Control Loop, Industry 4.0.

[1] Assistant Professor, Faculty of Science and Technology, Free University of Bozen-Bolzano, Bolzano, Italy, patrick.dallasega@unibz.it

[2] Research Associate, Fraunhofer Italia Research Società consortile a responsabilità limitata, Bolzano, Italy, carmen.marcher@fraunhofer.it

[3] Assistant Professor, Faculty of Computer Science, Free University of Bozen-Bolzano, Bolzano, Italy, elisa.marengo@unibz.it

[4] Assistant Professor, Faculty of Science and Technology, Free University of Bozen-Bolzano, Bolzano, Italy, erwin.rauch2@unibz.it

[5] Full Professor, Faculty of Science and Technology, Free University of Bozen-Bolzano, Bolzano, Italy, dominik.matt@unibz.it

[6] Head of Institute, Fraunhofer Italia Research Società consortile a responsabilità limitata, Bolzano, Italy, dominik.matt@fraunhofer.it

[7] Full Professor, Faculty of Computer Science, Free University of Bozen-Bolzano, Bolzano, Italy, werner.nutt@unibz.it

INTRODUCTION

Engineer-to-Order (ETO) processes with a successive installation on-site are very common in plant building and the construction industry. Here, every project is engineered, fabricated and installed according to a specific customer order. Traditionally, the Engineering, Fabrication and Installation departments work in separated silos, making the overall project optimization difficult. Big job orders are released, which induce high levels of Work-in-Progress (WIP) and hinder a parallelization of the three phases. Very often and especially in small and medium sized construction projects, the organizational execution planning is done only superficially. Among others, this can be explained by always-limited budgets for work planning. As a result, real-time information about the construction progress and a reliable demand forecast is always difficult to obtain, which are prerequisites for an on-demand delivery of ETO-components. According to Ballard and Howell (1998), "for construction crews, the largest categories of reasons for failures are missing materials and failure to complete prerequisite work." Usually, to avoid a lack of material on-site, which would cause construction interruptions, costly intermediate storages are used extending so the delivery time. Well-known approaches in research, like the Last Planner System (LPS) or the Location Based Management System (LBMS), are very useful to increase collaboration on-site and to improve the reliability of construction schedules. However, they have a limited impact on synchronizing the supply chain between the job shop fabrication and the construction progress on-site.

The approach presented in the paper describes how off-site and on-site production planning can be synchronized by means of a decentralized and pull-based control loop. The approach integrates three basic Lean Management concepts: Build-to-Order (BTO), Just-in-Time (JIT) and Pitch-Set-Flow. A first IT-prototype, which integrates the thinking and principles of Industry 4.0, like "Real Time Capability", "Decentralization" and "Self-Control", was developed and tested in an Italian company, which develops and realizes unique façade geometries and building envelopes planned by renowned international architects.

STATE OF THE ART

The LPS was developed by Ballard (2000) to *"decentralize decisions and empowering crews to plan and schedule detailed tasks"*. As important contribution to the traditional project management system, the LPS adds a production control component where the so-called Percent Planned Complete (PPC) indicator is measured (Ballard 2000). The PPC is computed by dividing the completed by the planned work. Thus, a high PPC value indicates a reliable construction schedule (Lincoln and Syed 2011). In the LPS assignments should be detailed enough to recognize if they were completed at the end of the week, but they have not necessarily to be coupled to construction locations (Ballard and Howell 1998). According to Navon and Sacks (2007), one of the limitations of the LPS is a weak or missing real-time construction progress measurement on-site as a fundamental precondition for coordinating trades on-site and the supply chain. To facilitate construction progress measurement, Kenley and Seppänen (2010) propose the so-called Location Based Management System (LBMS), which brakes a project in small locations and uses them to plan and control workflow. However, the focus of the LBMS is to coordinate construction works on-site and not to support a Just-in-Sequence (JIS) and Just-in-Time (JIT) delivery.

Supply Chain Management (SCM) can be defined as the material flow coordination within multiple tiers of suppliers to the customer, aiming at low inventory levels, low unit cost and short delivery times. It evolved in the manufacturing industry, side by side with the JIT-methodology, as one of the fundamentals of the Toyota Production System (TPS) (Shingo 1988). Today, Enterprise Resource Planning (ERP) systems are used as IT-support for SCM. Although, ERP-systems contributed mainly to the productivity increase of the manufacturing industry, the production planning functionality is most of the time centralized and based on the Material Requirement Planning (MRP) methodology (Hopp and Spearman 2001). MRP is based on the erratic assumptions of 1) infinite capacity levels of production lines and 2) constant lead-times (Hopp and Spearman 2001). The first one creates problems if the capacity reaches its limit, because lead-times are extended (Hopp and Spearman 2001). The second one is problematic because by using fixed values, one tends to use pessimistic or long lead-times to cope with uncertainty, which induces high inventory levels (Hopp and Spearman 2001).

Pull control mechanisms (as part of the JIT approach), like Kanban or CONstant Work In Progress (CONWIP), trigger the production based on the real demand and not just its forecast (Takahashi and Hirotani 2005). Furthermore, in Pull systems, WIP levels are measured and production is released accordingly. This is different from conventional Push systems (like MRP), where capacity, which is needed to release production, has to be estimated. Kanban is part specific and it is impractical to be used in non-repetitive manufacturing like job shops, which are common in the ETO-environment (Hopp and Spearman 2001). Otherwise, in CONWIP part numbers are assigned to a CONWIP card, which is allocated to a production line where every card should contain the same amount of work. This allows using CONWIP pull control mechanisms in a wide variety of manufacturing environments. Such Pull control mechanisms are originally based on physical cards and have been mostly used to manage production within companies. By using an appropriate IT-support, the connection between demand and supply can be extended to be used within companies. Especially, in the construction industry, it could allow to synchronize demand and supply between the site and the supply chain. The emerging research area "Industry 4.0" in Europe and as "Industrial Internet" in US (Bungart 2014; Evans and Annunziata 2012), paves the way for an on-demand production and delivery in construction supply chains. The term Industry 4.0 represents the so-called "fourth industrial revolution", which takes place in this era and proposes an IT-support for integrated manufacturing processes. Hermann et al. (2015) describe the major features of Industry 4.0 as embedded computers and networks (Cyber-Physical Systems (CPS)), which monitor and control physical processes connected over the Internet of Things (IoT). As a result, a gathering of steering information in real-time as well as a decentralized planning can be reached. Furthermore, by implementing frequent feedback loops within decentralized planning functionalities, a self-organization and self-control is pursued.

APPROACH DESCRIPTION

In Figure 1, the proposed approach is visualized schematically. The ETO market interaction strategy in construction consists mainly of three departments, which are connected in sequence (Dallasega et al. 2015b). The *Engineering* department focuses on the elaboration of shop floor drawings. Based on the shop floor drawings, the *Fabrication* department produces ETO-components. As a result, the *Installation* department assembles ETO-components into the building. Usually, coordination is based on a central *Master Schedule* resulting in a so-called Push system. Furthermore, these departments work in separated silos with big lot sizes. As a result, high and uncontrolled levels of WIP occur, extending the overall lead-time.

The approach we propose is based on a Pull mechanism from the construction site (Figure 1). Here, as soon as customer specifications are clear, the so-called Process Planning workshops take place, involving actors from design and execution (Dallasega et al. 2015c).

These Process Planning workshops are based on the Last Planner System (LPS), where the focus is given to the definition of the sequence of construction tasks preventing the so-called "chasing work" (Ballard and Arbulu 2004). During these workshops, based on the shop-floor drawings the necessary tasks on-site are identified. Furthermore, the sequence of work, which should flow from Engineering to the Installation on-site, is defined. As major difference to the traditional approach, where the amount of work released is based on the Master Schedule, in the proposed approach it is based on the levels of WIP between the Engineering, Fabrication and Installation departments.

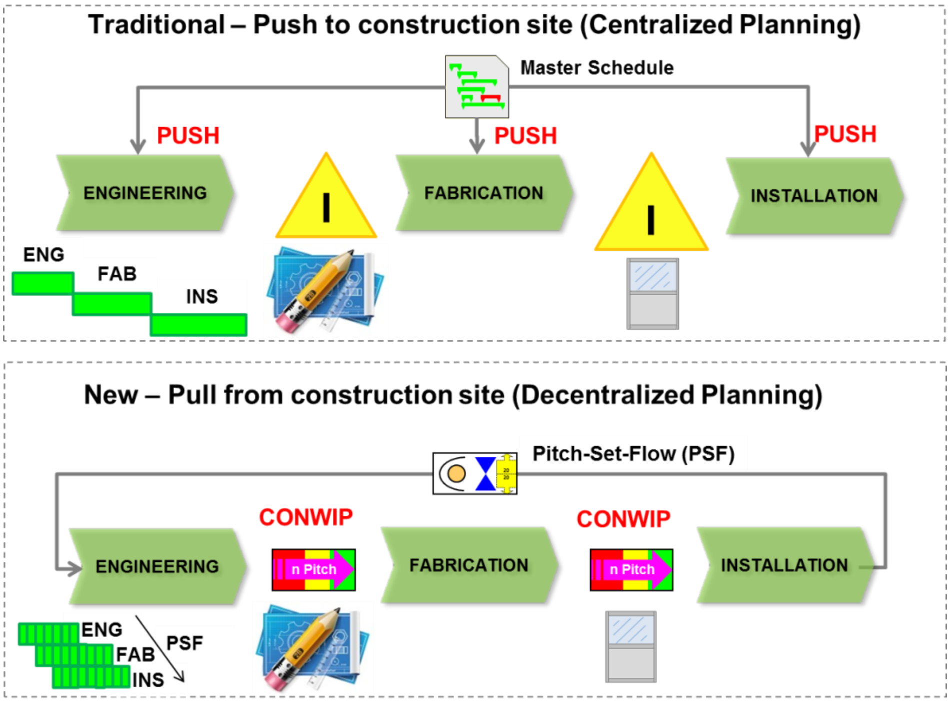

Figure 1: Pull from construction site in ETO

INCREASING THE DEMAND RELIABILITY ON-SITE

The fundamental principle consists of breaking down large job orders in approximately equal parts, to reach an optimal capacity saturation and minimal non-productive time throughout the supply chain and on-site. Here, the collaborative Process Planning workshops are organized, where actors from execution and design participate. Based on engineering drawings the installation process on-site is defined, in terms of tasks to be performed and dependences among them. For every task the so-called “Pitching” concept is applied, which is used for scheduling and monitoring the execution process. A “**Pitch**” defines the amount of **Construction Areas** (e.g., 2 rooms) which can be completed by a specific **Crew** (composed of a minimum number of workforce e.g. 4 workers) in a specific time **Interval** (e.g., 1 day or 1 week). The amount of “Pitches” is initially estimated by experts from execution, and then aligned to the customer demand by varying the number of crews. As a result, the customer demand is broken down into small lots with approximately equal size used to schedule and monitor the construction progress. Special emphasis is set on tracking physical parts of the building (Construction Areas). Furthermore, these workshops define the sequence of “Pitches” which should flow from Engineering to the Installation on-site. As a result, the so-called Pitch-Set-Flow (PSF) concept is applied, which defines the set of components, which should flow in one Pitch interval from fabrication to the site. This allows to parallelize the departments Engineering, Fabrication and Installation and so to drastically reduce the overall lead-time.
For a detailed explanation of the “Process Planning” and “Pitching” concepts, by means of practical case studies, please refer to Dallasega et al. (2013).

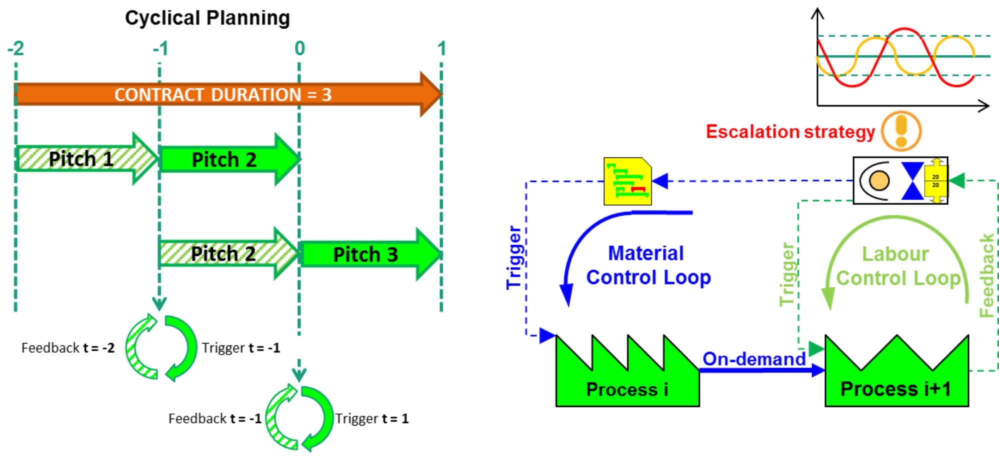

Figure 2: Increasing the demand reliability and self-regulation principle

To handle the high variance and the variability on-site, the so-called “Cyclical Planning” approach is used (Figure 2). It is based on the “Rolling Planning” approach, which is needed to handle the uncertainty of data in production planning, used in a wide variety of manufacturing industries (Stadtler et al. 2012). Here, when the first period of the planning horizon is finished a new planning period is added. When a plan has been generated and confirmed, the first planning period is called “*frozen period*” where no changes are allowed. This permits in the manufacturing environment to force that the planning is going to be implemented, avoiding a rescheduling of the following intervals.

As visualized in Figure 2, the scheduling of Pitch 2 (t=-1) should be based on the completion of Pitch 1, or in other words, according to the work performed in t=-2. Pitch 1, Pitch 2 and Pitch 3 should have approximately equal size and should fit within the contract duration. Furthermore, Figure 2 visualizes the self-regulation circuit by means of a customer-supplier relationship and two control loops. Considering the Labour Control Loop, the successor process i+1 (customer) triggers the work to be performed in the next time interval, according to the work completed in the previous time interval. Based on the scheduled and completed tasks (labour), the customer process (i+1) requests the needed material to the supplier process (i). The material control loop is based on the labour control loop, which means, if labour performance increases, the quantity of material requested increases. On the contrary, if labour performance decreases, less material is pulled from the supplier process (i). Of course, the demand increase and decrease should vary within a predefined corridor of flexibility (e.g. +/- 20% as visualized in Figure 2). If the demand variance exceeds the corridor of flexibility, an escalation strategy should be implemented by the responsible figures (e.g. the project manager).

COUPLING OF THE SUPPLY CHAIN TO THE CONSTRUCTION PROGRESS

Based on a reliable information about the customer demand, the supply chain is synchronized to the construction site. The construction progress is tracked in real-time and accordingly ETO-components are released JIS and delivered JIT from first-tier and second-tier suppliers. Status information of the supply chain and of the construction progress are available in real-time. As a result, the availability of ETO-components is considered in the scheduling process. This is needed to prevent a lack of material on-site and consequent construction interruptions.

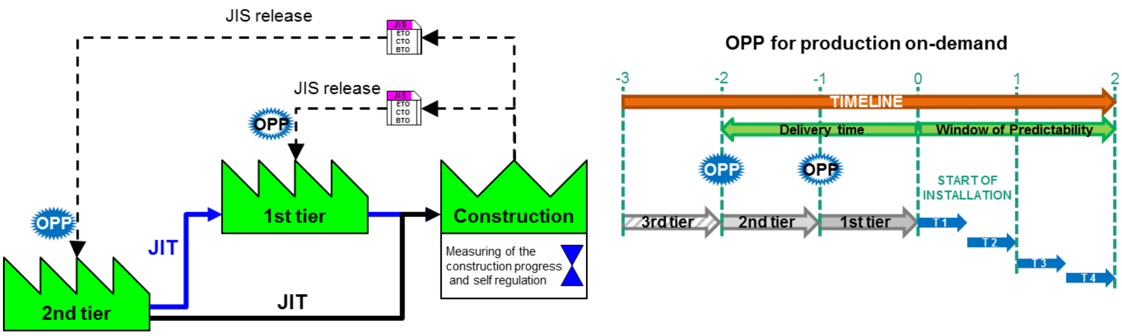

Figure 3: Synchronization of the supply chain to the construction progress

According to Ballard (1998), the delivery time should fit into the window of predictability and reliability on-site. This is especially challenging when considering ETO-components and multistage supply chains, both characterized by long lead-times. Figure 3 visualizes a two-tier supply chain, where the second-tier supplier delivers according to two alternatives: 1) ETO-components are delivered to the first-tier supplier for a last refining step and 2) ETO-components are delivered directly on-site for installation. Schweizer (2013) defines the Order Penetration Point (OPP) as the place in a manufacturing process where customer neutral production orders transition to customer related production orders. Considering Figure 3 (right), the window of predictability on-site consists of two time intervals (t=2). As a result, the OPP of first and second tier-suppliers should fit into two time intervals (e.g. 2 weeks). This allows triggering the supply chain based on the construction progress on-site, without intermediate storages.

PRACTICAL IMPLEMENTATION AND TESTING

The approach is implemented and tested in collaboration with the company Frener & Reifer GmbH (F&R). It is a medium sized company located in the north of Italy, acting as European leader in the delivery of high-class design facades. The implementation project consists of the new building Swiss Re Next at Mythenquai in Zurich (Switzerland), where F&R realizes the facades (Swiss Re Next 2016). The façade installation at Swiss Re Next started at the end of September 2015 and is planned to be finished at the end of April 2017.

The practical application of the pull-based control loop for on-demand delivery is shown in Figure 4. In this case, the window of predictability on-site consists of four calendar weeks (CWs). Since currently F&R works with a delivery time of more than four CWs, the fabrication process was mainly split in a prefabrication and an on-demand assembly and delivery to the site. A Lean Manufacturing (LM) supermarket is used to introduce an Assemble-to-Order (ATO) manufacturing system, suitable to follow the customer demand on-site. Furthermore, it is used to compensate the demand variability coming from site.

The Master Schedule links the processes upstream and downstream of the supermarket. It contains important milestones agreed with the customer and used to provide deadline constraints for the three departments. The Master Schedule was elaborated during the Process Planning workshops, where the responsible of the engineering department, the project manager and the installation supervisor participated. Based on the technology content, or in other words the façade type, the needed tasks for installation were identified in collaboration.

As visualized in Figure 4, the Labour Control Loop consists of scheduling (Trigger) and controlling (Feedback) the work processes within small time intervals. Based on the available capacity and on the scheduled tasks on-site, the material is requested from the supply chain. To guarantee that the right components are delivered in the right quantity, to the right location and at the right time, the final assembly is triggered according to the construction progress (Material Control Loop).

In the project, a weekly granularity for planning and control was used. The Cyclical Planning approach was used to schedule the working processes for the construction crews and to request the needed material. Every planning cycle consists of four CWs. At the beginning of CW41, the material needed for installation in CW44 is requested from the fabrication department of F&R. One week is needed for final assembly, one week to organize the transportation and logistics and one week before installation the requested material should arrive on-site. As soon as the material arrives on-site, the truck is unloaded and the material is disposed to the right Construction Area (within the levels of the building). At the same time, the delivery is controlled and checked in the IT-prototype. As soon as the scheduled week for installation is over, the construction progress is registered in the IT-prototype as a basis for the next planning cycle. The used IT-prototype was developed in Microsoft Excel. So far, a first web based application is going to be developed (Dallasega et al. 2015c). Furthermore, the company F&R is going to implement the IT-Prototype

(Microsoft Excel) in its ERP-system by extending a module needed for scheduling and monitoring the installation process and releasing the needed components on-site.

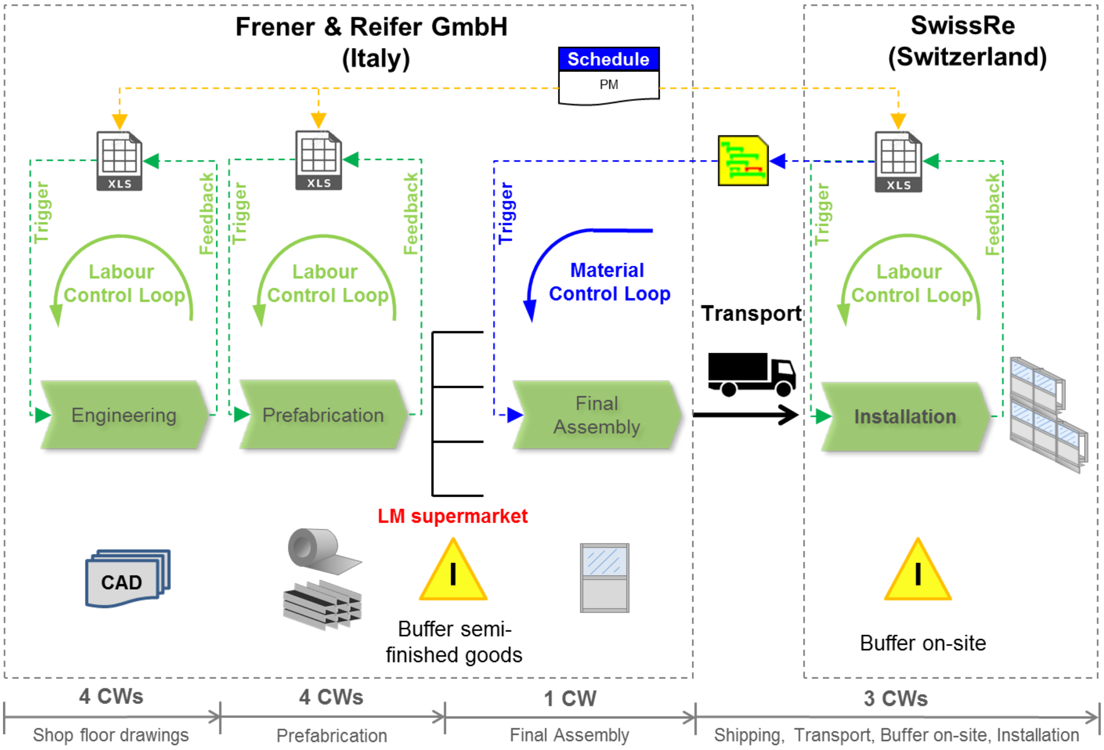

Figure 4: Testing of pull-based control loop for on-demand delivery within project SwissRe

As shown in Figure 4, the supermarket is placed between prefabrication and final assembly. As soon as the construction site is ready for installation, semi-finished components (stored in the supermarket) are assembled and delivered to the site for installation. The supermarket has a two-fold function: firstly, it allows minimizing the space needed for storing components and secondly, it permits to sequence production orders and the delivery to different construction sites.

IMPACT OF THE APPROACH

The first application of the approach was done at the Expansion Project Hospital of Bolzano. It showed that by spending **1 hour** for using the **methodology**, a working amount of **6 hours** could be **saved** (Dallasega 2016). As a result, a labour saving (on-site) of around 8% compared to the initial estimate could be reached (Dallasega 2016). Starting from September 2015, the methodology has been implemented and tested at the project Swiss Re Next in Zurich (Switzerland). According to the participating experts, the methodology allows to avoid traditionally problems like late or wrong material deliveries. Furthermore, thanks to the Labour Control Loop, problems can be identified early on and improvement actions can be taken in time, preventing so cost explosions. As a result, after seven months since the construction site started, the project is on budget according to the calculation department.

CONCLUSION AND OUTLOOK

To synchronize ETO-supply chains to the construction progress, the challenging part is to introduce a reliable demand forecast on-site. In this article, the “Pitching” concept was used to break down job orders in construction with approximately equal size, reaching low and controlled levels of WIP and at the same time short delivery times. As different from other industrial sectors, the construction industry is characterized by high variances especially on-site. To handle unpredictable events in an efficient way, the “Cyclical Planning” approach was introduced.

In future research, the approach will be extended to cover the entire building project. Specifically, the synchronization of Make-to-Order (MTO) supply chains within the phases of skeleton and interior construction will be considered.

REFERENCES

Ballard, G.H., 1998. Implementing Pull Strategies in the AEC Industry. *LCI White Paper 1*.

Ballard, G.H., Howell, G., 1998. Shielding Production: An Essential Step in Production Control. *Construction Engineering and Management Program*, University of California.

Ballard, G.H., 2000. The Last Planner System of production control. *Thesis submitted to the Faculty of Engineering of The University of Birmingham for the degree of doctor of philosophy*.

Ballard, G.H., Arbulu, R., 2004. Making Prefabrication Lean. In: *Proceedings of the 12th annual conference of the IGLC*. Denmark.

Bungart, S., 2015. Industrial Internet versus Industrie 4.0. Produktion-Technik und Wirtschaft für die deutsche Industrie. Available at: <http://www.produktion.de/technik/automatisierung/in-dustrial-internet-versus-industrie-4-0-338.html> [accessed 06.11.2015].

Dallasega, P., Matt, D.T. and Krause, D., 2013. Design of the Building Execution Process in SME Construction Networks. In: Thompson K, editor. *Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering*. Worcester, USA, June 28 – 29, p. 7-15.

Dallasega, P., Rauch, E., and Matt, D.T., 2015a. Increasing productivity in ETO construction projects through a lean methodology for demand predictability. In: *Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management*, Dubai, UAE, March 3 – 5.

Dallasega, P., Rauch, E., and Matt, D.T., 2015b. Sustainability in the supply chain trough synchronization of demand and supply in ETO-companies. In: *Proceedings of the 22nd CIRP conference on Life Cycle Engineering*, Sydney, Australia, April 7 – 9.

Dallasega, P., Marengo, E., Nutt, W., Rescic, L., Matt, D.T., Rauch, E., 2015c. Design of a Framework for Supporting the Execution-Management of Small and Medium sized Projects in the AEC-industry. In: *Proceedings of the 4th*

International Workshop on Design in Civil and Environmental Engineering, Taipei, Taiwan, October 30 – 31.

Dallasega, P., 2016. A method and IT-framework for On-Demand Delivery in Make-to-Order Construction Supply Chains. *PHD thesis submitted to the University of Stuttgart - Germany*.

Evans, P.C., Annunziata, M., 2015. *Industrial Internet: Pushing the Boundaries of Minds and Machines*. Available at: <http://www.ge.com/docs/chapters/Industrial_Internet.pdf> [accessed 06.11.2015].

Hermann, M., Pentek, T., Otto, B. 2005. *Design Principles for Industrie 4.0 Scenarios: A Literature Review*. Working Paper no.1.

Hopp, W.J., Spearman, M.L., 2000. *Factory Physics: Foundations of Manufacturing Management 2nd edition*. Boston: McGraw-Hill, pp. 698.

Kenley, R., Seppänen, O., 2010. *Location-Based Management for Construction - Planning, Scheduling and Control*. London: Taylor & Francis, pp. 125-128.

Lincoln, H.F., Syed, M.A., 2011. *Modern Construction – Lean Project Delivery and Integrated Practices*. Boca Raton - CRC Press.

Navon, R., Sacks, R., 2007. Assessing research issues in automated project performance control (APPC). In: *Automation in Construction*, 16(4), pp. 474-484.

Schweizer, W., 2013. Wertstrom Engineering – Typen- und variantenreiche Produktion. Berlin: epubli GmbH, pp. 53.

Shingo, S., 1988. *Non-stock production: The Shingo system of continuous improvement*. Port-land: Productivity Press.

Stadtler, H., Fleischmann, B., Grunow, M., Meyr, H., Sürie, C., 2012. *Advanced Planning in Supply Chains - Management for Professionals.* Berlin/Heidelberg: Springer, pp. 26-28.

Swiss Re Next, 2016. *An online documentation on the progress of the new building Swiss Re Next at Mythenquai in Zurich.* Available at: <http://next.swissre.com/en/> (accessed 05.04.2016).

Takahashi, K.M., Hirotani, D., 2005. Comparing CONWIP, synchronized CONWIP, and Kanban in complex supply chains. In: *International Journal of Production Economics,* 93 - 94, pp. 25-40.