Industry 4.0 Fostering Construction Supply Chain Management: Lessons Learned From Engineer-to-Order Suppliers

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Abstract—*Industry 4.0 will certainly transform the manufacturing industry but it will also have an impact on the construction industry and its connected supply chains. However, construction faces different problems than manufacturing. Often construction projects are highly customized, containing a significant numbers of engineer-to-order (ETO) components. ETO construction supplier companies consistently consist of off-site and on-site production elements. On-site construction processes are prone to high variability and unpredictability. This uncertainty makes supply chain synchronization for maintaining construction progress difficult. As a result, construction supply chains are characterized by high levels of intermediate buffers and long lead-times. We propose a variety of Industry 4.0 concepts to ameliorate these problems. Initial applications are identified from previous works. Additionally, we present some case studies for some lessons learned from the collaboration with ETO-companies. Seven action points in various applications of Industry 4.0 in the construction supply chain provide a guide to managers.*

Key words: Industry 4.0, supply chain management, construction, engineer-to-order, just-in-time

INTRODUCTION

INDUSTRY 4.0 represents the fourth industrial revolution after the mechanization, electrification and computerization of production environments (Kagermann, et al., 2013). It focuses on the increasing digitization and automation of the manufacturing industry especially by means of digital value chains between products, machines and operators. According to Wang (2018), Industry 4.0 will affect the manufacturing industry in a similar way as the smartphone technology did for the consumer world by broad behavioral and social changes.

Industry 4.0 is also transforming the construction industry and its supply chains. Although, the construction industry faces different concerns than the manufacturing industry when it comes to increasing productivity. Often, construction projects are characterized by a high number of participating companies with interrelated processes occurring at different stages and in different locations. Construction projects are usually unique, time limited and require a high degree of customization.

Construction Supply Chains (CSCs) usually consist of Make-to-Order (MTO) supply chains, where incoming material converges at a site where the building is assembled. CSCs are usually characterized by temporary initiatives, fragmentation, instability and high inefficiency.

A main CSC management objective is to plan and direct specific quantities of materials to the site where the final assembly takes place. According to the type of material assembled, different supply chain configurations can be considered: 1) Make-to-Stock (MTS) for consumables like bolts, 2) Assemble-to-Order (ATO) for components such as doors and windows, 3) Make-to-Order (MTO) for cast-in-place concrete or prefabricated panels and 4) Engineer-to-Order (ETO) for highly customized parts like design facades (Dallasega et al., 2018a).

For ETO manufacturing companies in the construction industry orders are engineered, produced, and installed on-site according to specific customer requirements (Rauch et al., 2018). Specific challenges of ETO companies are: 1) product complexity, 2) degree of customer product specificity, and 3) production and installation process complexity.

In the ETO environment, activities are partly performed on-site and therefore exposed to variability and unplanned events, such as changing weather conditions, customer requirements and labor resources (Dallasega and Rauch, 2017). It is difficult to foresee and forecast construction progress in this environment. This situation usually requires long lead-times. It is difficult to produce components on-demand and deliver them just-in-time (JIT).

Demand-oriented production and delivery of components is a key to avoiding the following problems: 1) late deliveries that cause construction interruptions due to missing material; and 2) early deliveries requiring on-site component storage, which increases risk of component damage and costs. Both early and late deliveries create non-value adding activities. In the first case, rescheduling of tasks and crews is needed, hindering an efficient on-site execution. In the latter case, there is additional effort for searching and handling of components.

Early or late component delivery requires excessive buffers of components on-site and within the supply chain, producing additional costs (Matt et al., 2014). These wastes create construction cost increases and budget overruns.

Early Industry 4.0 Applications in Construction Supply Chains

Industry 4.0 in the supply chain produces high potential to solve some of the inefficiencies that cause cost and delivery problems.

Limited Industry 4.0 understanding in the construction environment exists. Building Information Modeling (BIM) is one of the major construction industry digitization technologies. A major advantage of BIM is enrichment of the digital building model providing a variety of information including time, cost, energy efficiency component data, and field verified component on-site installation data. Construction industry developments have targeted the design and pre-construction planning phase; there are few investigations on how BIM supports the construction execution management process.

Industry 4.0 concepts in the manufacturing environment, such as Mobile Computing, Radio-Frequency Identification (RFID), Cyber-Physical Systems, Internet of Things, Internet of Services, Cloud Computing, Big Data, Augmented Reality and Virtual Reality have not been fully exploited, and have great potential, in the CSC industry (Dallasega et al., 2018a).

Some Industry 4.0 concepts have been applied to improve CSC management (Dallasega et al. (2018a). **Cloud based platforms** have been used to integrate data from suppliers, carriers, and contractors; allowing chain actors to share real-time information about construction materials status (Gong and Azambuja, 2013). Cloud-based collaboration integrates multiple sources in a system and this reduces the risk of out-of-date and incorrect information.

Web services technology that enables CSC partners to retrieve up-to-date information about the supply chain process (for example, delivery of materials) to avoid delays and re-work also exists. Information exchange among CSC partners is facilitated by using ontology-based web services (Das et al., 2015). They present a distributed database architecture that allows data replication to improve system reliability. Using CSC specific domain ontologies avoids data conflict and duplication.

M-internet, an Internet of Things and mobile technology example, has been shown to improve material flow and supply management, real-time information sharing, and communication, coordination and integration of CSC management. Mobile terminal devices, like personal digital assistants (PDA), integrated with global positioning systems (GPS) technology with RFID technology, increase CSC and on-site materials control (Shi et al., 2016).

Geographic Information System (GIS) have been used to automatically track and localize material throughout CSCs. Real-time information about the current location of materials throughout the supply, shipping and construction process is easily available (Majrouhi and Limbachiya, 2010).

GIS and **BIM** can jointly display the status of material throughout a supply chain and where in a building a material is used. Both Industry 4.0 concepts can provide warning signals for late deliveries. Moreover, the synchronization of interfaces between **GIS, BIM and mobile devices** improves material as well as information flow among CSC partners (Irizarry et al., 2013). BIM can be used to monitor CSCs. Data is collected in a cloud monitoring system and visualized using BIM.

RFID can be used to improve dispatching, receiving and inventory processes for technical trade and construction industries (Hinkka and Tätilä, 2013). Tasks related to identification and localization of materials can be automated; reducing the probability of incorrectly identified or shipped components. RFID systems improve construction schedule performance and reduce dependency on expensive intermediate storages. RFID technology allows gathering information about the CSC process in real time allowing for rapid response to unpredictable events.

Case Studies

We currently collaborate with different ETO supplier companies to optimize their processes using Industry 4.0 concepts. Some of these practices are outlined here.

An ETO building façade supplier uses Google sheets to track in real-time façade on-site installation progress. Each day the crew leaders record the completed tasks in specific construction areas, the number of installed components and the required/used work amount in terms of person-hours. Important key performance indicator computation occurs in real time each day. This allows early problem identification and timely improvement actions.

A web-enabled enterprise resource planning (ERP) system was developed allowing for visibility of materials status throughout the supply chain (for example, ordered, in production or shipped) and the release of the needed material on-site. As a result, component production on-demand and transportation Just-in-Time (JIT) to the construction site became possible. This situation eliminated wasteful intermediate storage; reducing lead times; a major achievement for an ETO based supplier.

A company producing shower cabinets developed a customized service management platform that runs on web-based tablets. The system allows for directly sending important information from the construction site to the company's production facility. As a result shorter delivery times and fewer orders of rework occurred, improving product quality.

Our research team currently collaborates with a number of ETO companies to investigate how the construction execution process can be connected to BIM for improved scheduling and CSC monitoring. This effort seeks data sharing from BIM models for planning and scheduling the execution process on-site. A major Industry 4.0 research collaboration focuses on importing construction progress data into the BIM model and visualizing it in an intuitive way. How the Industry Foundation Classes (IFC) file format supports an exchange between design and construction execution process information is also under investigation.

Lessons Learned From ETO CSC Companies and Opportunities for Industry 4.0 Applications

Lessons learned from ETO construction supplier companies application of Industry 4.0 technologies are now presented. These lessons can be valuable guidelines to managers who seek to implement Industry 4.0 capabilities in their supply chains. Figure 1 schematically summarizes some of these major points.

1) *Trigger the supply chain based on construction progress goals* (**TRIGGER JIT**):

The production process of first-tier and second-tier suppliers should be triggered according to meeting construction goals. This requires a detailed scheduling and reliable monitoring of the tasks to performed on-site. Usually on-site personnel are able to predict the tasks to be performed on-site not more than four weeks ahead (according to our observations). Thus, there is a

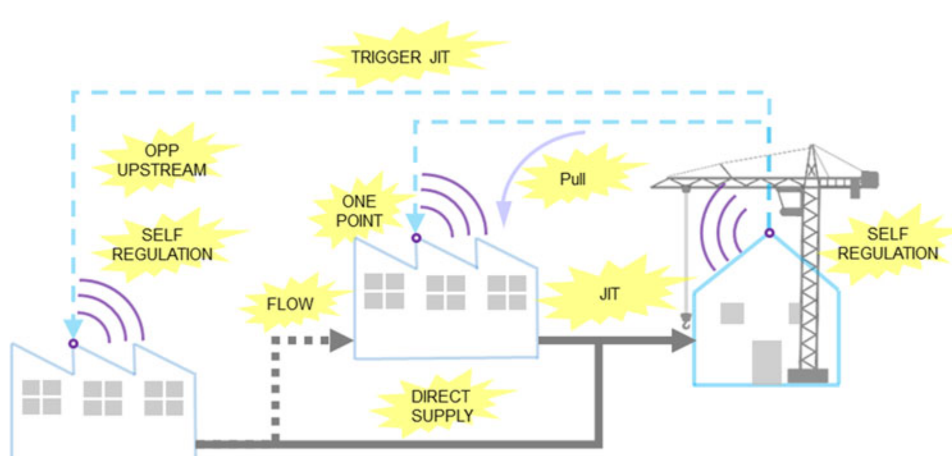

Figure 1. Action points for fostering CSC management with Industry 4.0.

"window of predictability", is the length of time for reliable prediction of tasks to be performed on-site; and this window is usually a trigger.

Two triggering strategies can be utilized.

a) If the delivery time enters the window of predictability on-site, the production start can be triggered directly;
b) If the delivery time does not enter the window of predictability on-site, the production has to be triggered in advance, according to the construction schedule, and buffered intermediately as semi-finished goods. As soon as the construction site is ready for installation, semi-finished components should be finalized (for example final assembly, packaging) and delivered to the site for installation.

As a result, JIT-supplies to the construction site become possible; avoiding high levels of work-in-process stock. By triggering the supply chain according to actual construction progress intermediate buffers are not created or overfilled.

2) *Supply material to the site according to customer demand (**PULL from site**)*

Based on the pace of the scheduled tasks on-site, their primary-, secondary- and tertiary demand should be defined. This activity can be completed by coupling construction schedules with bill of materials (BOM) of first- and second tier suppliers. A common strategy is to increase the labor resources on-site if construction has to be expedited. As such, more tasks have to be scheduled and completed, and this leads automatically to an increased request of material.

3) *Follow the customer demand (**SELF-REGULATION**)*

The customer process, in this case the construction site, controls the needed resources in terms of labor and material. This situation means that construction tasks have to be scheduled in detail and monitored in real-time; an important Industry 4.0 capability. A periodic forecast of required components on-site is performed. The work capacity on-site and within the supply chain is adjusted within a specific corridor of flexibility. As a practical example, consider working time increase or decrease by one day, which means working on a Saturday or stopping on a Thursday. This decision corresponds to a +/- 20% capacity flexibility. If the construction performance on-site increases or decreases, the delivery performance of the supply chain should be increased or decreased. If the increase is more then the capacity flexibility range, an escalation strategy has to be implemented by the planner.

4) *Trigger the supply chain in one point (**ONE POINT**)*

To avoid problems such as material delivery synchronization, the customer order should trigger the process chain only in one point. The order penetration point (OPP) defines the point in a manufacturing process where customer neutral production orders transition to customer related production orders (Schweizer, 2013). The placement of the OPP depends on the specific market interaction strategy. In MTS supply chains it is placed at the inventory of finished goods, in ATO at the final assembly process, in MTO at the first production process, and in ETO at the product engineering process.

5) *Let the customer order flow (**FLOW**)*

Downstream of the OPP, the order should flow in a continuous way to the customer. This means that intermediate interruptions and buffers should be avoided. In cases where this is not possible, work-in-process levels should be limited and just-in-sequence rules should be applied. In ETO supply chains the order flow should begin at engineering for fabrication until arriving on-site for installation. This requires that job orders be split into small batches of work. By releasing small work batches parallel process execution is possible. Parallel processing reduces overall lead-time and as such shortening delivery times. Lead-time reduction allows for staying within a window of predictability needed to trigger the supply chain, (see action point one).

6) *Supply components directly to the place of demand (**DIRECT SUPPLY**)*

Project specific components should be delivered directly to the place of demand. If the primary or secondary demand of construction components does not require prefabrication, they should be delivered directly to the construction site. This process avoids wasteful intermediate storages throughout the supply chain. Moreover, an uncoupling of the supply process from manufacturing allows to parallelize processes and again to reduce the overall delivery time.

7) *Move the OPP upstream the supply chain (**OPP UPSTREAM**)*

The OPP should be moved upstream the supply chain (first-tier, second-tier and so on), until the overall delivery time enters the window of predictability on-site. This process allows for agile reaction to on-site changes; preventing to build up excessive amounts of buffer or delaying construction.

A practical implementation requires reorganizing processes; preferably through lean management principles. Industry 4.0 concepts can support and foster the reorganization of processes. Currently, we are collaborating with ETO companies to develop a tool based on mobile computing and connected with BIM that implements this action point process model.

Issues and Limitations

When following the seven guidelines proposed here, managers should be aware of the following issues and limitations.

The tradeoff between low levels of stock throughout the supply chain, reached by JIT deliveries, and the potential increase of deliveries can raise transportation costs and environmental impact (CO2 emissions).

Similar to most traditional mature industries, there is an adverse cultural attitude within the construction industry to accept new processes and technologies. Here, the stepwise qualification of employees should not be forgotten. In our experience, when implementing innovative tools in practice, a good course of action is to assure that the reorganization of processes goes hand-in-hand with the introduction of new technology. This assures that the company is ready to adopt the new technology. As a practical example, providing foremen with assistants having knowledge of information technology may be necessary to build organizational expertise and acceptance. This approach allows for shortening the initial learning phase and at the same time it assures that the system is fed with valuable data; and management is strongly supportive by supply needed resources.

Managers should not forget the costs that may incur due to the reorganization of processes. Initial increased effort to handle new technology and needed qualification to increase the acceptance degree of employees; basic change management concerns.

Investment decisions should also consider the compatibility degree of new technology (like BIM or M-internet), with existing technology (like ERP systems). All these costs may increase the time new technology pays back and influence the decision whether or not to invest in Industry 4.0.

Further Considerations and Conclusion

Usually construction projects are unique, time limited and require a high degree of customization. ETO construction supplier companies consist of off-site and on-site production processes.
Construction sites are usually characterized by high variability and unpredictability. This characteristic makes the synchronization of supply chains to the construction progress difficult. As a result, expensive construction stops due to missing materials and other types of waste like searching, excessive moving and handling of material are frequent in CSCs.

Industry 4.0 concepts seem to be very promising in addressing the various ETO construction supply chain deficiencies.

It has been shown that Industry 4.0 concepts can help address these deficiencies and synchronize the supply chain to construction progress. Seven action points are proposed as guidelines for managers to improve CSC processes. These processes can be supported through Industry 4.0 technologies and systems.

Future issues include more broadly encompassing sustainability aspects, beyond the business aspects. CSCs have not been very efficient from an ecological perspective. For example, a significant delivery and transportation in the construction industry is been performed by trucks (Akan et al., 2017). This partice could be explained by weak planning and monitoring of construction progress, requiring flexible transportation schedules and short delivery times. Reliable planning and measurement of construction progress is a prerequisite for economic and ecological production and delivery of components.

Defining sustainable supply cycles in the construction, infrastructure and plant building industry are all needed. Different intermodal freight transport systems with the final aim to reduce CO2 emissions and foster environmentally friendly freight transports will be required. Questions on what extent a delivery of construction components can be completed by rail, using distribution centers and supplying the last mile by alternative energy vehicles with environmental-friendly fuels needs evaluation. Consideration of new distribution center designs, Industry 4.0 technology and construction site locations require further developments.

How to further increase flexibility of the supply chain through: a) space saving at the place of consumption (on-site) and b) increasing supply chain reaction to meet high variability of construction processes is still needed. Further technological forecasting, maturity mapping, requirement analyses and specification of construction logistics IT-platform are all needed. These Industry 4.0 platforms need to support configuration and plans for CSC. Economic as well as ecological key performance indicators need further development and monitoring.

Further case studies to evaluate the feasibility of these concepts and the Industry 4.0 tools as they evolve, along with the necessary incentives and support from public policy, for a long term technological road mapping can greatly benefit the CSC and other industries.

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