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LEAN MODULAR INTEGRATED CONSTRUCTION MANUFACTURING: OPERATION-BASED PRODUCTION PROCESS OPTIMIZATION

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Abstract

Modular integrated construction, as one of the innovative approaches of modular construction, has the most complex production process and a high level of customization. Although moving into the factory and proving its efficiency through many practical cases, MiC manufacturing has its uniqueness and still has great potential to be further optimized to improve productivity. This paper proposes an operation-based process optimization framework for MiC manufacturing to assess and improve the leanness of the production system through simulation and optimization. This framework can evaluate the leanness of the production system and optimize the production process and management.

Introduction

Modular construction has been seen as one of the opportunities to improve productivity in the construction industry by shifting the traditional on-site construction to a manufacturing-style production system, with various benefits including reducing the construction schedule and cost, improving labor safety, and cutting carbon emissions (Bertram et al., 2019; Gann, 1996). Modular integrated construction (MiC) is one of the innovative approaches of modular construction, which is a free-standing integrated module with completed finishes, fixtures, and fittings (Wuni & Shen, 2020). The integration production makes MiC manufacturing more complex and different from other modular construction techniques such as prefabrication, whose main products are mainly 2D panels and frameworks (Hussein et al., 2021). MiC manufacturing is conducted module by module and can be seen as a horizontal and independent construction project in the factory, different from the giant and vertical on-site construction project.

MiC manufacturing is recognized as a combination of the manufacturing industry and the construction industry. On the one hand, the in-factory production environment reduces some uncertainties at the construction site such as weather effects and safety concerns, and improves the work parallelism since the on-site foundation work can be conducted at the same time as the module manufacturing, which significantly reduces the project duration (Abdelmageed & Zayed, 2020). On the other hand, MiC manufacturing still follows a similar construction process as conventional construction such as the workflow, procedures of construction activities, and operation tools (Zhang et al., 2020). Meanwhile, MiC manufacturing has a high level of customization, and different projects can have different modular designs, sizes and construction materials (Nahmens & Ikuma, 2012). Currently, MiC manufacturing mainly has primary production line and machinery, which has lagged far behind the advanced manufacturing industry. Overall, MiC manufacturing process is constrained by the long-established traditional construction methodology and practices, which prevent the industry from moving forward (Assaad et al., 2022).

To overcome these limitations, many efforts have been done in previous studies. From the technological aspect, many studies explored the application and improvement of software and hardware in the production process to improve the level of automation and standardization (Zhai et al., 2019). From the managerial aspect, lean theory and its related tools have been considered as a major approach to improving the productivity of MiC manufacturing(Yu et al., 2013). Lean theory is developed from Toyota production system, of which the main goal is to minimize waste in the production process including surplus of production resources, overproduction, surplus of inventory, and worthless capital investment (Sugimori et al., 1977). However, MiC manufacturing is an order-based production and does not need to predict the market demand (Mas' udin, 2007). Therefore, lean theory for MiC manufacturing is mainly adopted to reduce the production time and improve productivity (Goh & Goh, 2019).

There is a research gap of previous studies. The previous lean-related optimizations mainly used the circle time in the workstation as the objective, which was suitable for prefabrication or pre-cast building components. For MiC manufacturing, the workstation-based optimization cannot focus on every production operations especially when factory adopts a fixed position layout for production. Therefore, this research proposes an operation based process optimization framework for MiC manufacturing to assess and improve the leanness of the production system through simulation and optimization. This research will scale down the optimization objective from workstation to production operation, which is more applicable for the production of heavy, large, complex, and customized MiC module.

Literature review

Modular integrated construction manufacturing

MiC is an innovative construction approach whereby free-standing volumetric modules are manufactured in a prefabrication factory and then transported to site for installation in a building (Darko et al., 2020). There are different modular construction products having different production complexities. According to the component shape and the pre-finished and pre-furnished level, modular construction products can be divided into nine categories. Compared with other modular construction products, MiC module has the most complex manufacturing requirements and longest production time with complete finishes, fixtures, and fittings, as shown in the Figure 1.

Figure 1: Production complexities for different modular construction products (referred to Pan et al. (2021)'s work)

Different status of the complex MiC module has different production configuration in the factory. For the material processing, 2D panel, and 3D assembly framework, the related production activities can be completed in different workstations, and then gathered to the total assembly station to complete the structural framework. For wall installation, painting, and MEP fixing, there are two types of production approaches. One is to put the module on a giant rack with a pulley to convey the module. The giant rack can have different areas to finish different production activities. Another approach is to put the module in a fixed position to complete multiple activities in a single workstation. For renovation, furniture, and packaging, the production duration is long, and the operation is complex. Therefore, a fixed position production is more applicable. This uniqueness of MiC manufacturing makes it difficult to monitor the processing time of every production operation when multiple operations are conducted in a single workstation.

However, previous studies of process optimization are mainly production line-based or workstation based which are not applicable for fixed position production and cannot evaluate the production process of the detailed production operation (Yu et al., 2013). For example, RFID system is a popular data collection technique in many studies (Altaf, 2016), however, it does not work well in MiC manufacturing especially when factory adopts a fixed position layout for production. The operation-based production process optimization for MiC manufacturing is limited in the literature.

Lean theory and leanness evaluation

Lean production is to employs teams of multi-skilled workers at all levels of the organization and uses highly flexible, increasingly automated machines to produce volumes of products in enormous variety (de Wardt, 1994). The concept of producing products in a 'lean' manner was first introduced by a research group at MIT after studying Toyota Production Systems (TPS) in the 1980s (Womack et al., 1991). Although reportedly effective at Toyota, a large portion of the TPS tools are problem-specific and difficult to follow precisely by practitioners (Wan & Frank Chen, 2008). TPS has two pillars, which are "Just-in-time" and "autonomation". "Just-in-time (JIT)" basically means to produce the necessary units in the necessary quantities at the necessary time, and "autonomation" may be loosely interpreted as autonomous defects control that supports JIT by never allowing defective units from a preceding process to flow into and disrupt a subsequent process (Sugimori et al., 1977).

The term "leanness" was interpreted diversely in the literature. Naylor et al. (1999) used "leanness" to describe the process of realizing lean principles, and Comm and Mathaisel (2000) stated that "leanness is a philosophy intended to significantly reduce cost and cycle time throughout the entire value chain while continuing to improve product performance". Bayou and De Korvin (2008) thought Comm and Mathaisel' s definition only emphasized the input dimension of leanness, therefore they presented an improved one according to Womack et al. (1991) 's work. They defined leanness as a strategy to incur less input and produce better output, where 'input' refers to the physical quantity of resources used and their costs, and 'output' refers to the quality and quantity of the products sold and the corresponding customer services" (Bayou & De Korvin, 2008). This definition covers both the efficiency and effectiveness of manufacturing performance, where efficiency represents the relationship between input and output and effectiveness represents the relationship between output and the organization's goals (Vinodh & Chintha, 2011).

Various lean assessment surveys have been proposed to guide users through lean implementation, among which the lean enterprise self-assessment tool (LESAT) developed by the lean aerospace initiative (LAI) at MIT is among the most popular (Nightingale & Mize, 2002). However, the existing assessment approaches share a common weakness in that the surveys are inevitably subjective due to individual judgments. Besides the assessment approaches, the quantitative lean metrics to track the effectiveness of improvement efforts also concern the leanness level (Wan & Frank Chen, 2008). For example, Detty and Yingling (2000) applied simulation models with several performance metrics to quantify the potential benefits of lean implementation. Among the existing lean metrics, manufacturing cycle efficiency (MCE), an index for cycle time reduction, compares value-adding time with total cycle time to show the efficiency of a manufacturing process, representing the leanness level in terms of time-based performance (Zavacki, 2003). Next, the value-added efficiency index (Fogarty, 1992), labor productivity (Katayama & Bennett, 1999), operation leanness, and new-value creativeness (Leung & Lee, 2004) are identified or proposed to measure the leanness level of the manufacturing process. However, an integrated assessment and optimization approach, to measure the leanness of MiC manufacturing and to optimize the production process based on operation analysis, are limited in the literature.

Methodology

To improve the leanness and productivity in MiC manufacturing, this paper proposes an operation-based process optimization framework to first assess the leanness of the production system via an integrated evaluation approach and then improve it through simulation and optimization. As shown in Figure 2, the core of this framework lies in three parts: 1) the operation-based production process work breakdown structure (WBS) and data collection; 2) the integrated leanness assessment approach; 3) the operation-based simulation and optimization to improve the leanness of production process.

Production process breakdown and data collection

WBS is one of the fundamental approaches used in the construction industry to manage building projects (Garcia-Fornieles et al., 2003). WBS can help project managers break down the giant project into smaller work packages for various purposes such as resource allocation, cost estimation, and schedule control (Zhang et al., 2020). In the on-site construction project, work packages are conducted floor-by-floor with consistent work breakdowns. However, in MiC manufacturing, work packages are conducted module-by-module and can vary differently according to the facility layout design and production configurations. For example, different production activities can be conducted at different workstations or be integrated at one fixed workstation. Therefore, production line-based or workstation-based WBS can vary significantly in different MiC projects due to the high level of customization, but operation-based WBS has better consistency since the general workflow in a MiC module is similar even with different sizes and designs. For a well-produced MiC module, this paper proposes an operation-based production process breakdown structure including three levels. Level 1 measures the total production time of a MiC module to examine the JIT delivery to coordinate with the on-site installation and the learning effects during the repetition.

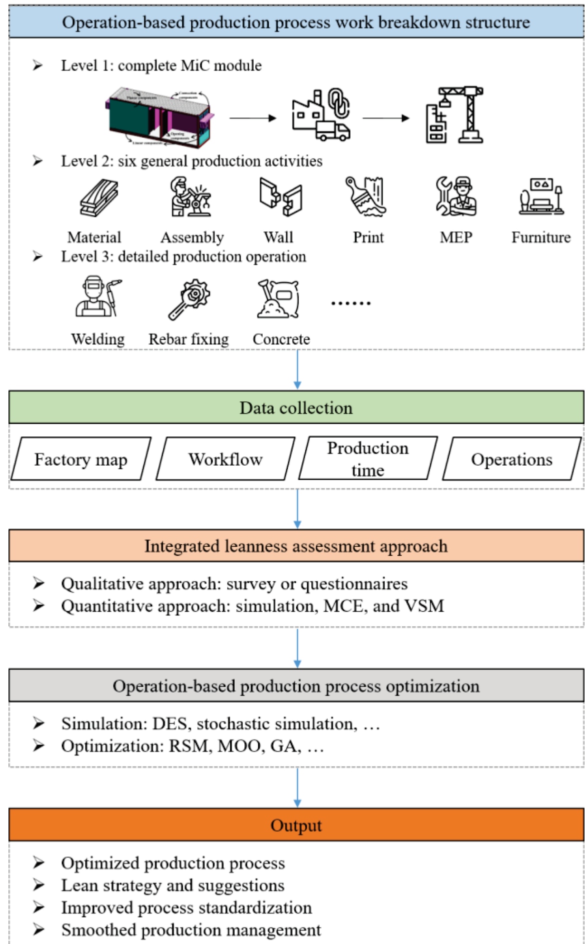
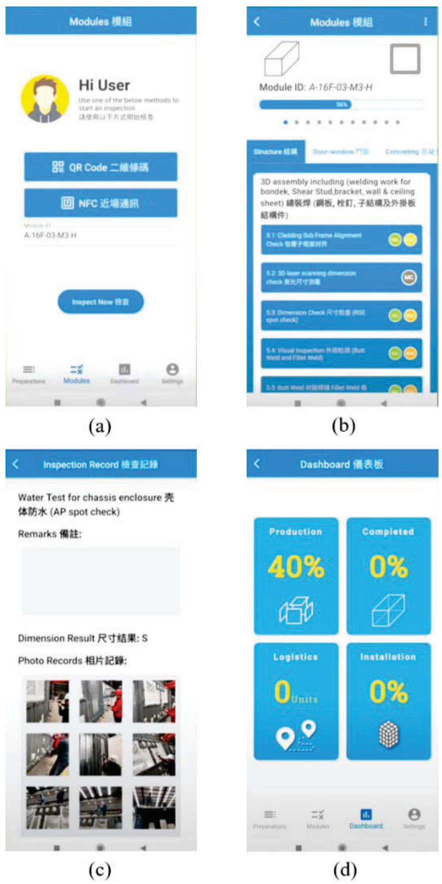


Figure 2: The operation-based framework

Level 2 focuses on six general tasks including material processing, 2D and 3D assembly, wall-related installation, printing, mechanical, electrical and plumbing (MEP), and renovation and furniture to measure the production performance at the same time achieving a better generalization for different projects. Level 3 analyzes more detailed production operations in these six categories to find the production problems and idle time in the production process. At this level, the specific operations in different categories may vary a bit according to different designs of MiC modules.

Data collection is conducted using an e-inspection mobile phone application, named e-Instar developed by our team, and detailed production records, if applicable, collected from the factory. For the e-Instar application, the inspection tasks are set based on the production operation, therefore, once the production operations are settled, inspection tasks can be generalized accordingly. After the operation is finished, inspectors will check and record the status of module. As shown in Figure 3, inspection tasks are input and encoded into the App for the inspectors in the off-site factory to record the real-time inspection results and upload them into the database. Inspection photos are also uploaded in a thumbnail format to the database together with the inspection records. The recorded inspection information mainly involves the module ID, inspection task ID, the inspection task, the timestamp of the inspection, the inspection result, and the associated photos/videos. The timestamp of the inspection, once it passes, can be referred to as the work time/duration of the activity.



(a) (b) (c) (d)

Figure 3: The e-Instar application

Integrated leanness assessment approach

Lean assessment is to define the current leanness level of the production system, which represents the first step of all proposed implementation frameworks (Almomani et al., 2014). To evaluate the leanness and find the production problems in the production system, this paper proposes an integrated leanness assessment approach to combine a qualitative approach such as a survey or questionnaire with a quantitative approach such as simulation models of performance metrics, MCE, and value stream mapping (VSM) to assess the production system focusing on the detailed production operations. Characteristics of MiC manufacturing and different production operations will be identified by the leanness assessment. Different leanness indicators will be compared in the experiment and validated through a case study.

Operation-based production process optimization

According to the leanness assessment results, simulation and optimization can be conducted to solve the identified production problems and smooth production operations. Response Surface Methodology (RSM) is a series of experimental design, analysis, and optimization technologies that originated in the work by Box and Wilson in 1951 (Hill & Hunter, 1966). The main goal of RSM techniques is process optimization, which could be applied, for example, to minimize the cost of operation of a production process, to minimize the variability of quality characteristics, or to achieve desired specifications for a response. In order to optimize an industrial process, RSM methods suggest building a parametric model for the expected response using designed experiments.

Discrete event simulation (DES) is a method used to model real-world systems. Each event occurs on a specific process and is assigned a logical time (a timestamp). The result of this event can be an outcome passed to one or more other processes. The content of the outcome may result in the generation of new events to be processed at some specified future logical time.

For MiC manufacturing, production is conducted module-by-module, and the module production is independent, especially after the 3D assembly. Therefore, simulation and experiments can be conducted with reasonable assumptions and validated through a case study to examine the practical contribution.

Case study

To validate the proposed framework, a case study is conducted based on a real-life project. This typical MiC project uses the strategy of designing in the head office, manufacturing in the Pearl River Delta (PRD), and assembling onsite back in Hong Kong. Such projects are dominated by clients and managers familiar with project design and onsite management and increasingly, with cross-border logistics and supply chain.

This project comprises two 17-floor towers on top of a 3-level podium, as shown in Figure 4(a). The podium and the major structural parts (e.g., core wall) of the two towers adopt traditional cast in-situ construction while the rooms and toilets adopt MiC technique. 1,200 MiC modules are produced in the factory with around 50 production operations and more than 23 thousand inspection data in the dataset. As shown in Figure 4(b), the production is conducted in the factory with a primary production configuration.

a) The outlook of the project

b) A snapshot of the factory (Source: authors, 2023)

Figure 4: The focal project

Discussion

The manufacturing part of a modular construction project plays an important role in the success of the project since it directly affects the schedule, cost and quality. MiC manufacturing, having the most complex production requirements, is constrained by the long-established traditional construction methodology and practices. To improve the productivity and production management in MiC manufacturing, this paper proposes an operation-based framework to assess and improve the leanness of the production system using simulation and optimization. Compared with previous studies, this paper focuses more on detailed production operations rather than production lines or production workstations due to the uniqueness of MiC manufacturing.

To scale down the optimization objective and achieve scientific management, a three-level production process breakdown structure is proposed to organize work packages for MiC manufacturing. This work breakdown structure can help analyze the performance of the production process and the learning effects of the repetitive activities. To explore the potential of lean implementation in MiC manufacturing, an integrated leanness assessment approach is proposed to evaluate the level of leanness in the production system. This assessment can also help identify the characteristics of MiC manufacturing and current production problems and difficulties in the production process. With the assessment results, simulation and optimization can be conducted accordingly to improve the level of leanness and productivity in MiC manufacturing.

To achieve better practical contribution, more real-life cases should be conducted to further validate and optimize this framework. How to generalize the leanness optimization approach and the related findings to other modular construction projects also needs more exploration.

Conclusions

Modular construction is having a trend of a renaissance with its advantages of reducing the construction duration and uncertainties, but at the same time, it is also a challenge for construction project managers to control and manage the manufacturing process. To overcome the challenge, lean theory and its related tools have been considered as a major approach to controlling the project and improving the productivity of MiC manufacturing. However, MiC manufacturing has its own uniqueness, the parallel production activities in a single workstation, which makes the production line-based or workstation-based process optimization not applicable to monitor the processing time of detailed production operations. Therefore, this paper proposes an operation-based process optimization to analyze the characteristics and achieve scientific production management.

The assessment and optimization results can benefit the improvement of productivity and standardization for MiC manufacturing. With this framework, practitioners can evaluate the production performance of the production system, and optimize the production process to achieve smoother production operation and less idle time. From the perspective of the construction industry, the results can benefit the improvement of leanness and project control.

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