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Autonomous production tracking for augmenting output in off-site construction

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ABSTRACT

Problems in existing methods of production tracking in off-site construction result in schedule delays and increased costs. To eliminate these deficiencies, an autonomous production tracking that analyzes real-time production data is proposed. A specific implementation of the proposed production tracking mechanisms has been developed for a large off-site construction plant in Australia, and is in the process of installation. The paper shows that: (i) The production model in off-site construction is always nonlinear in the outcome due to the presence of variability (ii) in systems with a periodic production target, deviation from the schedule converges to zero at the end of production period and the same downward trend should be followed in designing plan buffers and (iii) long-term production performance in off-site construction can autonomously be monitored and controlled by observing critical variables of production. The paper provides those who manage off-site construction with recommendations on effective production tracking and management. The models and propositions in this research are of practical value and can be used to detect impending production shortfalls against periodic targets in the short-term, and adjust capacity parameters and production targets in long-term planning.

1. Introduction

Off-site production (OSP) is an increasingly popular approach in construction that relocates some on-site operations to a more controlled factory environment. OSP is a unique hybrid of manufacturing and construction and can be described as a series of construction operations on a progressive assembly line. It offers several advantages over traditional site-built construction such as superior quality [1], swift delivery [2], improved health and safety [3], and customization capability [4]. The competitive advantage of off-site manufacturers over their on-site counterparts has its roots in different factors such as broad adoption of information technology, modern equipment, and innovative production layouts.

Although OSP is the fastest growing segment of the construction industry [5], there are production challenges that hamper its performance. These production challenges are related to high levels of product mix [6], traditional supply chain configurations [7], engineering faults and rework [8], management decisions [9], and cyclic market demand [10]. Adverse effects of these production challenges are eventually translated to the manufacturing floor and together with process dependencies generate bottlenecks. Delays are closely associated with bottlenecks as there are frequent work starvations downstream and blockages upstream [11]. Delays create a gap between planned production and actual output and prevent OSP making scheduled commitments. Real-time production tracking in OSP must provide short term information (e.g. by hour or shift) regarding progress towards production targets and long term information (e.g. by day or week) regarding capacity parameters and demand planning [12].

The necessity of providing a production tracking system with both accurate short term and long term outputs highlights the importance of developing tailored mechanisms that can evaluate the real-time production performance in off-site construction. This requires detection of impending shortfalls with regard to the production target and updating production plans in accordance with operations-level changes occurring on the manufacturing floor. To this end, this paper describes a customized methodology for production tracking in off-site construction as the most important part of managing workflow in any production environment (shop floor control). First, a description of previous studies is provided to identify gaps resulting in previously presented research. Next, a model of production output in off-site construction is developed and the underlying mathematical background is briefly explained. Then, empirical data is used to detect impending production shortfalls against periodic targets in short-term planning.

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Finally, long-term capacity tracking and feedback mechanisms in off-site construction are discussed and related propositions are developed.

2. Research background

Although production planning and control systems have been widely investigated by researchers [13–15], there is still much scope to develop customized systems that are tailored for the unique conditions of the construction industry [16,17]. Traditional techniques for construction planning and control are only able to manage stationary bottlenecks. Such techniques are too coarse and often require an excessive number of jobs under construction to prevent work starvation of the bottleneck [18]. Previous research suggests borrowing production initiatives from manufacturing and the use of workflow leveling strategies such as 'even flow production' in construction [19]. Although useful, such initiatives are too restrictive for production planning in off-site construction. In fact, they are more appropriate for highly repetitive processes of house building [20,21]. Furthermore, they cannot manage floating bottlenecks that are closely related to different designs and product mixes in off-site construction [11].

Despite efforts in developing specialty production tracking systems for off-site construction, the industry has found the available systems unsatisfactory especially for large scale production. Mullens [22] indicates that realizing the fundamental differences between on-site and off-site construction is crucial to developing robust production control systems that work effectively on the manufacturing floor. For instance, resources in off-site construction are dedicated to processes and therefore the 'parade of trades' [23] proceeds quicker than in on-site construction. Furthermore, demand in off-site construction is usually translated to a periodic production target (quota) and it is non-trivial to measure the real-time progress towards these targets. Hence, the early detection of an impending production target shortfall is pivotal to identify timely corrective measures in off-site construction production.

A number of researchers have studied the development of production tracking mechanisms for site-built construction. For instance, Arditi et al. [24] suggests the use of linear scheduling methods and line of balance to orchestrate the completion of work units at approximately the same rate. Production planning under resource constraints has also been explored in the context of on-site construction [25–28]. Furthermore, object-oriented models have been developed for projects with highly repetitive processes such as house building [29,30]. However, there is little research that has explored the potential of developing customized production tracking mechanisms for off-site construction that can generate real-time feedback on the progress towards periodic production targets to adjust capacity parameters [31,32]. In the next section, the process of autonomous production tracking in off-site construction will be discussed.

3. Research method

Empirical research is conducted in this paper in order to analyze the impact of using an autonomous production tracking system on output in off-site construction. After reviewing relevant studies in the construction literature, the nonlinear model of production in off-site construction is developed and analyzed using conditional probability or Bayesian inference. The analytical model focuses on computing posterior probabilities of meeting scheduled targets given observations of production performance. Translating into probability language, let B = "probability of missing the scheduled target"and A = "a positive deviation from production plan". The objective is to calculate P(B|A) and the Bayes' basic formula can be used for this purpose:

$$P(B|A) = \frac{P(B \cap A)}{P(A)} = \frac{P(B \cap A)}{P(B \cap A) + P(B^c \cap A).} \quad (1)$$

Where $P(B^c)$ is the probability of meeting (not missing) the scheduled production target. The multiplication rule is used to compute the probabilities on the right side of the equation:

$$P(B \cap A) = P(B) \times P(A|B). \quad (2)$$

Details about the analytical modeling approach are presented in Section 4 of the paper. Following the analytical modeling of production tracking in off-site construction, empirical data is used to construct discrete event simulation (DES) experiments and detect impending production shortfalls against periodic targets in both short-term and long-term planning.

A large off-site construction plant in Australia was selected and several site observations were conducted to collect required production data. The off-site construction company builds several sizes and types of precast concrete tanks for industrial wastewater treatment plants. In the controlled environment of the plant, different products are made by placing concrete in reusable formwork and curing it to maximize strength and minimize permeability. All products comply with ACI 318-14 standards and are superior to cast-in-place concrete tanks in terms of construction time, durability, and resistance to development of stress fractures. Fig. 1 illustrates a simplified representation of an activity cycle diagram for building precast concrete tanks.

The off-site production data of particular interest in this research are processing times, instances of production shortage/overage, different product mixes, and availability of plan buffers. In order to have a fair comparison between production scenarios, three factors of production rate, resource availability, and rework rate were controlled for throughout the experimentation. In addition to site observations, automatic collection of real-time data in construction was conducted by using wireless data collection tools such as ultra-wideband (UWB) receivers and tags. Using UWB facilitated the implementation of the proposed production tracking system and tracing production input and output on the manufacturing floor to accurately compute real-time values of critical production variables. The process of using the collected data to construct analytical models and simulation experiments are explained in details in the following sections of the paper.

4. Mathematical representation of production tracking in off-site construction (shop floor control)

The development of a tailored tracking mechanism for off-site production (OSP) is motivated by two important considerations. In the short term (e.g. by hour or shift) the main objective is to detect impending production shortfalls early enough so that timely corrective measures can be implemented to remedy the problem. In the long term (e.g. by day or week), information provided by the production tracking system is used for adjusting capacity parameters and periodic targets of construction production. There are two commonly used set of techniques in OSP for tracking and management of production. The first set includes network analysis techniques such as Critical Path Method (CPM) and Project Evaluation and Review Technique (PERT), which have dominated the industry. Efforts have been made to strengthen and improve these techniques [33,34]. However, they will almost certainly result in biased production models in OSP as interactions between resources are not fully captured and their main focus is on scheduling, not causing events to conform to the schedule [35,36].

The second set of techniques for tracking and management of production in OSP focuses on managing workflow in the production environment (shop floor control). The aim of this set of techniques is to form a decision support system that suggests feasible sequences for production processes and also address the issue of bottleneck management [37]. Furthermore, the shop floor control system is usually equipped with a real-time simulator of off-site construction processes that traces high priority (hot) jobs in the network and adjust capacity parameters accordingly. This approach to production tracking is the