CAUSES AND PENALTIES OF VARIATION - A CASE STUDY OF A CONCRETE SLAB PREFABRICATION SHOP

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ABSTRACT

Concrete precast plants require strict control over and adherence to the timing and sequence of operations. Variation for this research is divided into the variation in task starting time (the difference between the planned and the actual starting time) and the variation in task duration (the difference between the planned and the actual task duration). This study determined causes of variation in task starting time and duration of precast concrete slab production tasks and used STROBOSCOPE simulation techniques to demonstrate the penalties associated with not reducing variation, which are 1) overtime, 2) Work in Progress (WIP) increase, 3) cost overrun, and 4) labor productivity decrease. It was found that simply taking managerial actions, such as keeping workers waiting or busy, is insufficient for managing variation and effort should be put to reduce variations and make plan more reliable. The results could help prefabricators to understand the causes and penalties of variation, which is the starting point of attacking and reducing variations.

KEY WORDS

Variation, causes, penalties, concrete slab prefabrication, lean construction.

INTRODUCTION

While precast concrete offers significant potential advantages in cost, speed of erection, and quality, it is challenging for concrete prefabricators to produce made-to-order concrete products that can be delivered to a site when needed. In order to reach the above goal, a major challenge that a concrete prefabricator faces is handling variations during the fabrication process in the job shop. Due to the detrimental impact of variation on production performance (Hopp and Spearman 2008, Tommelein et al. 1999), Ballard et al. (2003) noted that the first line of defense advocated by lean construction is to reduce variation in an effort to reduce waste and ultimately increase production performance. Hopp and Spearman (2008) identified causes of variation and developed strategies to reduce variation in the manufacturing environment. The Last Planner^{TM} System (LPS), which focuses on reducing the

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negative impacts of variability and increasing the reliability of workflow, has been developed and successfully implemented in construction projects to improve planning and production performance (Ballard and Howell 1994, Ballard 2000, Ballard and Howell 2004). However, few research efforts have examined causes of variation in terms of how the factors affect construction related task starting times and duration. Additionally, little research has been done in quantifying the penalties of variations. Modeling and understanding causes and penalties of variation, which falls under the umbrella of lean construction (Howell 1999), is essential to improve system performance, and hence critical to effective production management (Hopp and Spearman 2008).

LITERATURE REVIEW

Among the many definitions of variability or variation in construction research, Howell and Ballard (1994) measured variability of work flow by comparing the tasks assigned (what "will" be done), to those completed (what "did" get done). Rilett (1998) defined variability as the variance associated with a component or end product specification in construction projects. Tommelein et al. (1999) defined work flow variability as the standard deviation from an expected average. Koskela (2000) defined variability as the random variation in the processing times or arrival of inputs. Radosavljevic and Horner (2002) defined variance in construction labor productivity as a standard deviation, a measure of dispersion from the mean. Thomas et al. (2002) calculated variation of productivity as the average of the absolute value of the difference between daily productivity and baseline productivity. In this study, two types of variation are defined:1) the variation in task starting time (the difference between the planned task starting time and the actual task starting time) and 2) the variation in task duration (the difference between the planned task duration and the actual task duration). The planned task starting time and duration are set in the production schedule, so that variation is not from an average, but from a target (what was planned).This definition provides a direct means to measure the variation and allows more detailed observation and analysis of the causes of variation.

Regarding the causes and detrimental impacts of variation on production systems, Hopp and Spearman (2008) identified causes of variability and they argued increasing variability always degrades the performance of a production system. In the construction arena, Tommelein et al. (1999) presented a parade game to demonstrate the impact of work flow variability on a single-line production system, which revealed that unreliable work flow results in unutilized production capacity and larger intermediate buffers when high variability prevails. Thomas et al. (2002) compared the impacts of output variability and variability in labor productivity on project performance. The results showed that variability in labor productivity is closely correlated to project performance.

METHODOLOGY

A prestressed hollow core slab prefabrication plant was chosen for the case study because an off-site concrete slab manufacturing system is typical in the construction prefabrication domain. Stroboscope (Martinez 1996) simulation parameters were based on the initial in situ observations and the project manager's interviews. Data collection sheets were tailored for the second site visit, which covered a period of 7 days. Detailed production data included site layout, schedule and twenty one sets of actual and planned task starting time and duration data for each of four tasks, 1) cutting and removing slabs, 2) cleaning the bed, 3) pulling and stressing strands, and 4) placing concrete. The causes and consequence of variations, when and how the problems are resolved were also documented. The data collected during the second site visit was used for analysis of causes of variation on task starting time and duration, and as inputs for simulation to test the penalties of variation on production system performance.

CASE STUDY

PROJECT BACKGROUND

Our work is based on a North Carolina precast concrete components prefabricator. Figure 1 illustrates the layout, showing three 400-foot casting beds aligned from south to north. A quantity of cables for 2 weeks usage, equipment (i.e., cutting saw, extruder, hydro cylinder), and tools (i.e., spade, broom, steel tape, sponge, enamel) are stored and accessible to laborers at the point of use. To the west of the shop, there is a concrete batch plant where concrete materials are mixed and transported by an overhead bucket riding along the rails. Regarding the fabrication process, the laborers clean and oil the beds and pull strands with a hydraulic cylinder. Each strand is tensioned individually. The number and size of the strands vary depending on the slab design. Then an overhead bucket transports a one cubic yard batch zero slump concrete from the batching and mixing plant automatically to the correct place using an overhead bucket gantry and then discharges the batch into the extruder.The extruder vibrates, compacts, and creates the hollow-core slab as it moves along the rails of the bed. As the extruder continues to form the slab, a laborer marks the slab where it needs to be cut. Once the concrete has reached 70% strength, which takes about 6.5-10 hours, the slab can be cut as required. The slab pieces are then picked up by an overhead crane and loaded onto a flatbed truck for a quality check. Following this, the slabs are transported to a local storage yard for delivery to the job site.

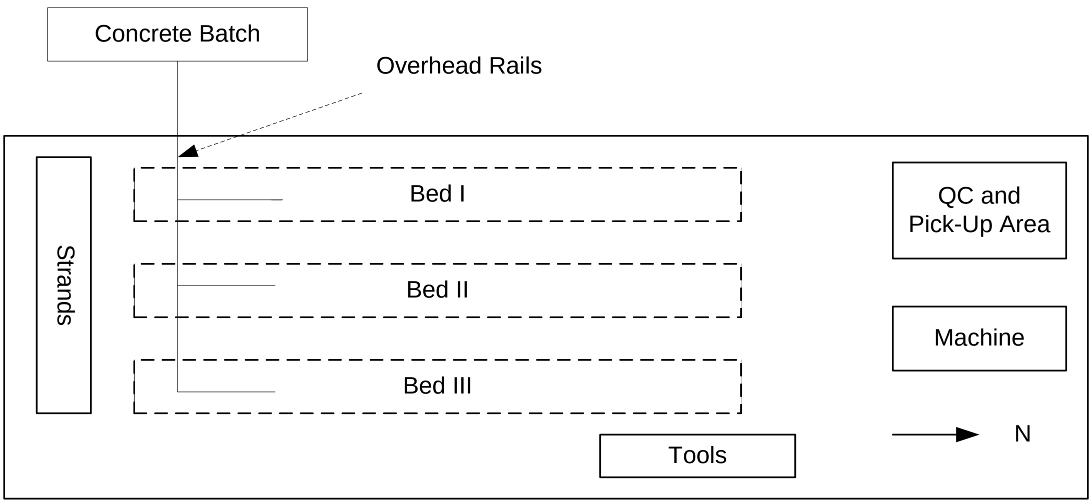

Figure 1: Hollow Core Slab Fabrication Shop Layout

According to the schedule, one supervisor, one foreman (F, see in Figure 2) and four laborers (L1, L2, L3, L4), work in the shop. The foreman, laborer 1, and laborer 2 work from 4:00 AM to 2:00 PM and laborer 3 and 4 work from 5:00 AM to 3:00 PM. Each worker works 4 days a week. The foreman and four labourers work contents are shown in Figure 2. The supervisor manages the entire team and also does kitting (i.e., checking the availability of drawings, materials, and tools) for the precast element. Figure 2 illustrates production schedule for a typical day. The task duration of cut and remove varies among the three beds. This is because each bed was planned to have a different work complexity level. Usually bed III is the easiest to cut so that work can speed up after the first bed. Cutting and removing bed I has the longest duration, because cutting saw often malfunctions after cutting beds III and II; these malfunctions tend to be mechanical problems, such as vibration and friction. At the end of each day, three beds have been placed with concrete, so as to cure before the next day's production. The schedule was used as the benchmark to calculate task starting time and task duration variations.

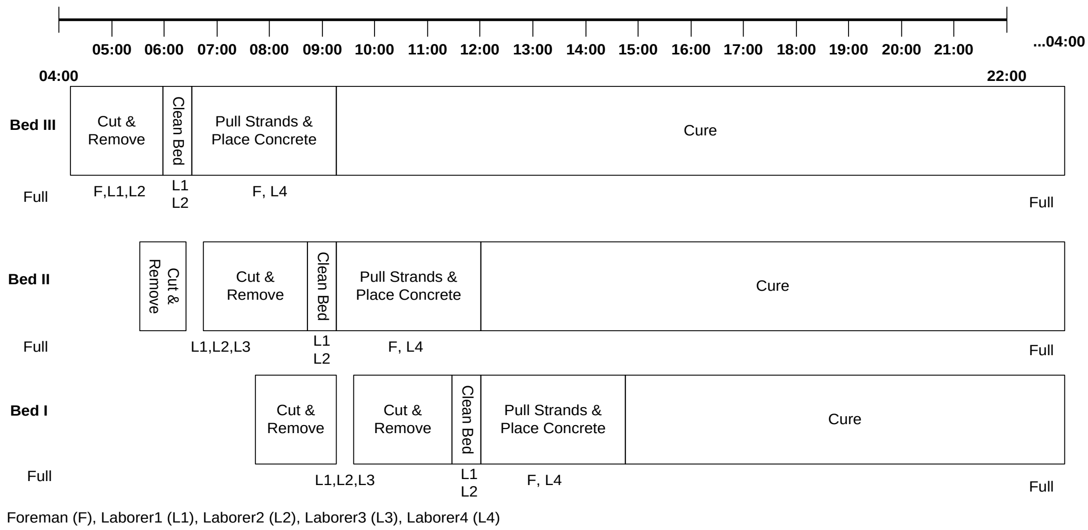

Figure 2: Production Schedule

DESCRIPTIVE ANALYSIS

Figures 3 and 4 provide the cumulative starting time and duration variation (summed over 7 days) where both positive and negative variations were observed. Cut and remove and place concrete, two major value-adding activities in this prefabrication process, cause major task duration variation. Cut and remove was further divided into Design I, II, and III according to design and work complexity. In this study, the prefabricator produced three types of slabs which were all 6'' in thickness, 1) standard rectangular slab, 2) rectangular slab with a rectangular notch in the corner, and 3) rectangular slab with a rip in the middle. For standard slabs, the saw cuts along the width direction of the bed only, making it of the lowest complexity level. The complexity level increases for slabs with a notch in the corner, as the saw needs to change direction to complete the cut. Slabs with a rip in the middle are of the highest complexity level as the saw needs to both change direction and move back and forth when it moves along the rails of the bed. Design II mainly consists of slabs with a rip in the middle, Design I slabs with a notch in the corner, and Design III standard rectangular slab; thus making the complexity level decrease from Design II, I to III. Figure 4 shows that the design complexity tends to cause more variation on task duration. Regarding task starting time variation, clean bed varies the most, since it is the successor of cut and remove. That is, higher duration variation in predecessor leads to higher starting time variation in successor.

Regarding the causes of variation, factors in eight categories were reviewed: prerequisite work, detailed design/working method, labor force, tools and equipment, material and components, work / jobsite conditions, management / supervision / information flow, and weather or external conditions. Table 1 and Table 2 show the major causes of variation in task starting time and task duration based on the site visit. Prerequisite work plays the most important role in causing task starting time variation. Regarding task duration variation, tools/equipment causes variation in task duration, which adds up to about 6.35 hours. Variation in task duration caused by tools/equipment include waiting for overhead bucket(1.12 hours), overhead bucket breakdown(1.4 hours), overhead crane breakdown (1.05 hours), cutting saw breakdown (1.78 hours) and malfunction of cutting saw due to mechanical problem (1 hour). The second major cause of task duration variation is work complexity (about 3.68 hours).

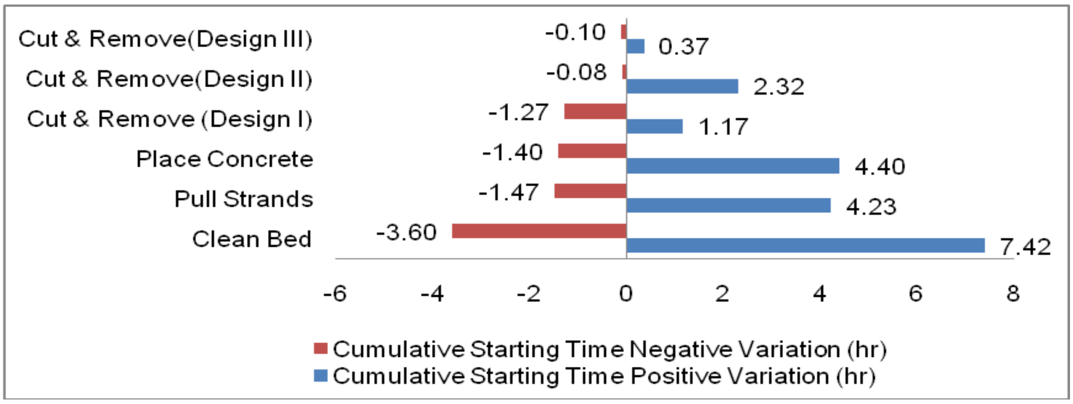

Figure 3: Cumulative Starting Time Variation

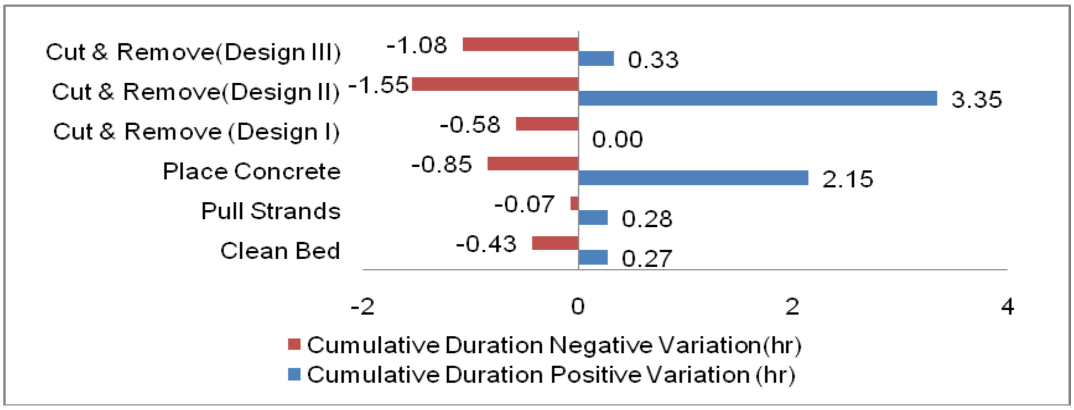

Figure 4: Cumulative Duration Variation

Table 1: Major Causes of Variation on Task Starting Time

Category	Factor	Tasks Affected	Cumulative Variation(hr)
Prerequisite Work	Prerequisite work isn't completed.	All	19.78
Prerequisite Work	Prerequisite work is done earlier.	All	-8.08
Tools/Equipment	Waiting for overhead bucket	Place Concrete	1.00
Labor Force	People arriving late	Cut & Remove	0.20

Table 2: Major Causes of Variation on Task Duration

Category	Factor	Tasks Affected	Cumulative Variation(hr)
Labor Force	Adding more labor	Clean Bed	-0.86
Prerequisite Work	Rework	Pull Strands	0.03
Material and Components	Error in concrete water content	Place Concrete	1.12
Tools/Equipment	Waiting for overhead bucket	Place Concrete	1.12
Tools/Equipment	Overhead bucket breakdown	Place Concrete	1.40
Tools/Equipment	Overhead crane breakdown	Cut & Remove	1.05
Tools/Equipment	Cutting saw breakdown	Cut & Remove	1.78
Tools/Equipment	Malfunction of cutting saw due to mechanical problem	Cut & Remove	1.00
Detailed Design/Working Method	Work complexity	Cut & Remove	3.68

CAUSE ANALYSIS

During the previous site visit from January 25-28, and February 2-4, when a time difference in task starting time or duration was identified, the reasons associated with it were also tracked. Actually, we asked the question of "why the variation occurred?" twice in the process of tracking variation and its associated causes. The answer to the first why question led us to identify one or more of the categories (i.e. Tools /Equipment) where the problem arose and the answer to the second why question further recognized the specific reason under the aforementioned category(i.e. Waiting for overhead bucket). In addition, cumulative starting time or duration variation in terms of a particular cause could be calculated by adding the time differences under that cause category. It was how we obtained the figures in Table 1 and Table 2 in the paper. In order to identify the causes of task starting time variation and task duration variation and pinpoint specific method to reduce variation and improve productivity, another site visit was conducted in April 2010. We asked project manager, supervisor, and foreman "why the identified problem happened?" again to pinpoint the causes of variation. Table 3 showed the 3 tiers of causes identified through site observation and interviewing project manager, supervisor and foreman.

SIMULATION MODEL DEVELOPMENT

Both descriptive statistics and project manager's interviews suggest that equipment breakdown is one of the major causes of variation in task duration. The prefabricator has one extra machine for each equipment type except for the overhead bucket; thus once the equipment breaks down during production, the extra one could be utilized immediately for emergency use. Consequently, there is not much loss in terms of time and productivity. The simulation in our study models the breakdown of overhead bucket when no extra equipment is available. The assumptions of this model are: 1) an overhead bucket is used in the shop; 2) for different scenarios, work content is the same: three beds are cut and placed concrete for each iteration; 3) the overhead bucket breaks down before the task place concrete starts; 4) the estimated repair time is 2 hours, which is based on the project manager's input(during the 7-day observation period, two breakdowns associated with overhead bucket were observed; one lasts for about 2 hours, while the other was about 15 minutes); and 5) two execution policies when the overhead bucket breaks down are simulated, namely keeping the laborers waiting and keeping the laborers busy by sending them to other tasks.

Table 3 Causes for Starting Time and Duration Variation

Variation Type	1st Tier Cause (Category)	2nd Tier Cause (Factor)	3rd Tier Cause	Countermeasure
Starting time	Prerequisite Work	Prerequisite work isn't completed.	N.A.	N.A.
Starting time	Prerequisite Work	Prerequisite work is done earlier.	N.A.	N.A.
Duration	Prerequisite Work	Rework	Human error	Labor training, QC carefully checking
Duration	Labor Force	Adding more labor	Accelerating task duration	N.A.
Starting time	Labor Force	People arriving late	Employee policy not strictly enforced	Strict enforcement of employee policy
Duration	Material and Components	Error in concrete water content	Human error Changing weather	Labor periodic retraining
Starting time/ Duration	Tools/Equipment	Waiting for overhead bucket	Batch operator not paying attention, Material blockage, Computer problem	Hiring experienced batch and extruder operator
Duration	Tools/Equipment	Overhead bucket/crane breakdown	Bucket shoes coming out of the power line Ceiling electrical cable breakdown	Checking the power line and ceiling electrical cable regularly
Duration	Tools/Equipment	Cutting saw breakdown	N.A.	Checking the saw every day
Duration	Tools/Equipment	Malfunction of cutting saw due to mechanical problem	Vibration, friction and bad burn in the drive	Freezing up the burn
Duration	Detailed Design/Working Method	Work complexity	Different slab designs	Appropriate combination of work on each bed

In this model, the laborer can be sent to task cut and remove to help move the slabs from casting bed to the QC and pick-up area. And either keeping laborers waiting before preconditions are ready or keeping laborers busy by sending them to help other tasks were management actions taken in the face of variation. Both policies didn't include reduce variation. Based on project manager's experience, task duration for cut and remove could usually be reduced by 25% when one or two laborers are added. Figure 7 shows the simulation model developed by Stroboscope system. Table 4 demonstrates different simulation scenarios categorized by different overhead bucket breakdown spots.

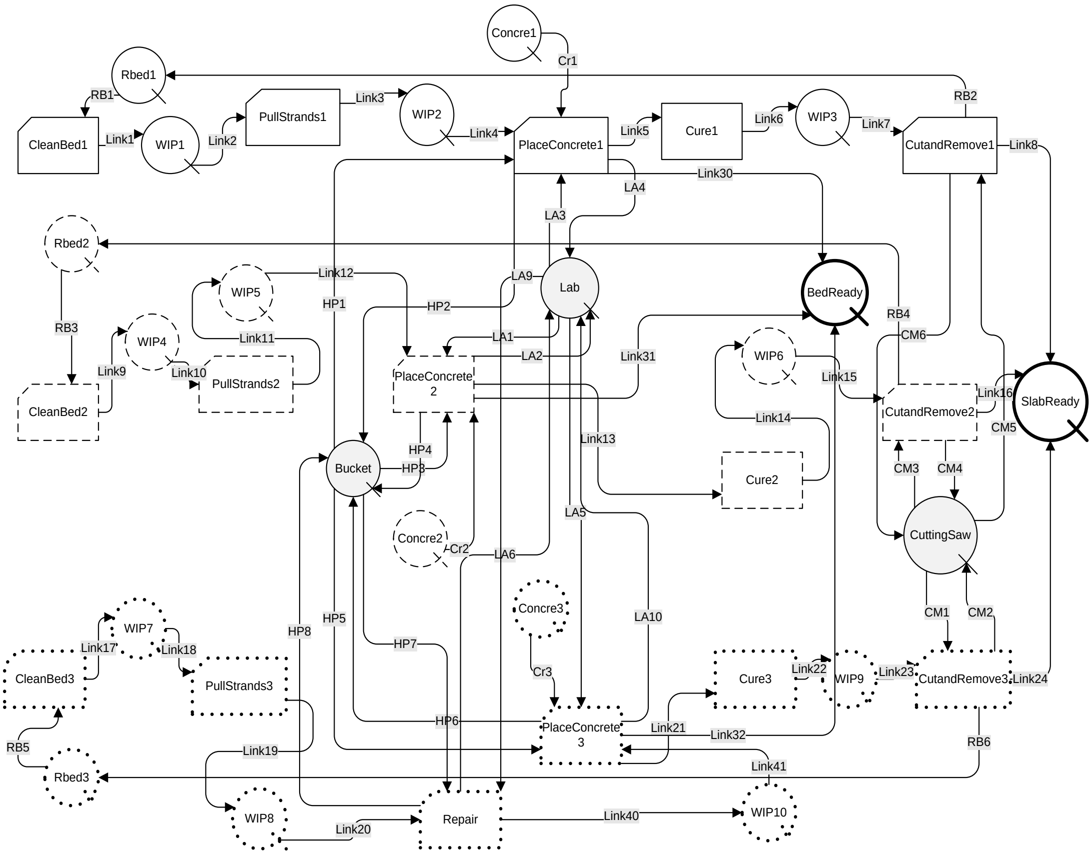

Figure 7: Stroboscope Simulation Model

DIFFERENT EXPERIMENTS AND DATA ANALYSIS

Table 5 shows the simulation result of 1000 iterations for different scenarios. Multivariate analysis of variance (MANOVA) and t-test were conducted to determine whether the differences of duration and WIP are significant among different scenarios. The tests showed WIP[4] values between any two scenarios are significantly different at the confident level α=0.05. Scenarios could also be divided into four subgroups according to different overhead bucket breakdown spots (N.A., bed III, bed II, and bed I, see Table 4). Duration values are significantly different among subgroups at α=0.05, and within-subgroup duration is not significantly different. The simulation results in Table 5 demonstrate penalties associated with not reducing variation in terms of overtime, WIP increase, cost overrun and labor productivity decrease using Scenario 1 as a benchmark. The overtime indicates the later the bucket breakdown occurs during a day, the longer delay it causes. Overtime leads to productivity

[4] WIP is the summation of all average content of WIP_i , i=1,2,3....9, which is generated by Stroboscope simulation software.

decrease and cost overrun determined by the five workers' overtime pay with the rate of $15/labor hr. WIP increase shows the build-up of work ahead of a crew. The simulation modelled only one variation cause, equipment breakdown, and hence penalties would be much more severe if different variation causes act together in reality. The simulation showed that neither keeping laborers waiting before preconditions are ready nor keeping laborers busy would solve the problem the equipment breakdown causes. Furthermore, keeping laborers busy policy would lead to an increase in WIP which may cause new variation and lead to more detrimental effects on production system performance.

Table 4: Simulation Scenario

Scenario No.	Bucket Brkdown Spot	Hypothetical Remedy (Labor Policy)	Potential Output
1	N.A.	N.A.	N.A.
2	Bed III	Waiting at Bed III	Labor idle
3		Moving to Bed II	Cut & Remove 2 duration decreases by 25%
4	Bed II	Waiting at Bed II	Labor idle
5		Moving to Bed I	Cut & Remove 1 duration decreases by 25%
6	Bed I	Waiting at Bed I	Labor idle
7		Moving to other beds	N.A.

Table 5: Simulation Result (1000 iterations)

Brkdown	Scenario	Duration (min)	WIP	Productivity (sf/h)	Overtime (min)	WIP Increase	Cost Over
N/A	1	677	0.57	74.5	0	0.00	$0.00
Bed III	2	732	0.73	68.8	56	0.16	$69.49
	3	730	0.79	69.0	54	0.22	$66.88
Bed II	4	750	0.61	67.2	74	0.04	$92.13
	5	752	0.68	67.0	76	0.11	$94.60
Bed I	6	797	0.49	63.2	121	0.08	$150.94

CONCLUSIONS

The paper identified causes of variation in starting time and duration of precast concrete slab production tasks based on field observation and used simulation to determine penalties associated with not reducing variation in terms of an increase in project duration, WIP and cost and a decrease in labor productivity. The simulation indicated that neither keeping laborers waiting before preconditions are ready nor keeping laborers busy could attack variation and on the contrary keeping laborers busy policy may contribute to or cause more new variation indicated by WIP increase. The findings would help concrete prefabricators to understand keeping laborers waiting or keeping laborers busy is insufficient for managing variation and effort should be put to reduce variation and make plan more reliable.

Identifying causes and penalties of variation is the starting point of variation reduction and this paper showed field observation and simulation an effective method to determine causes and penalties of variation. Although the findings of this study are based on a slab production facility, this research can have a broader impact on the construction industry as the methods described in this study can be applied to other fabrication processes as well. While this research demonstrated the penalties associated with not reducing one type of variation, equipment breakdown, future research should be conducted to investigate the impact of other possible causes on production system performance and also how the prefabrication shop can better adapt to demands variability which is an important external source for variation. Future research should also be conducted to develop strategies to reduce variation based on the identified causes of variation.

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