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Reducing variability of workforce as a tool to improve plan reliability

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Abstract

Variability of flow is recognized as one of the greatest obstacles to production management. Since the work flow and labour flow are two dominators of work performance, it is important to manage them simultaneously. The objective of this paper is to examine if an increased plan reliability could be reached by reducing the variance of a labour flow. Therefore, three different construction labour data sets have been examined by utilizing Monte Carlo Simulation, to analyze the probability to finish simulated projects within a certain time. The research findings revealed that reducing variance of the workforce flow does not necessarily shorten the project length, nevertheless it increases probability to finish the tasks within a critical path duration. Additionally, it was concluded, that reducing the variance of crew allocation can improve the productivity.

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Keywords: Lean construction; Plan reliability; Flow; Reliability.

1. Introduction

Variability is a common issue in construction management due to the fact that one-of-a-kind-nature-product, fixed in site, and temporary-organizations characteristics, consequently gives rise to changeable and variable conditions [6]. The theory of lean is introduced to the construction industry to maximize the value to the client and to minimize the waste. Lean recognizes that the variability is an obstacle inducing poor performance in production [12]. Recent researches

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indicate that using lean techniques can improve the flow reliability, which could lead to better performance [16]. For instance, the most applied lean construction tool, the Last Planner System, is developed to better tackle variability to improve the work flow reliability by shielding upstream, thereupon, contributes to higher percentage of planned activities completed (PPC) [2,3,4,7]. It is crucial to improve the reliability of work flow in the initial phase. To put it simply, reduction of work flow variability can keep the production system under control, just as the Last Planner System revealed, one of the most important rules is sizing a work to match the capabilities of a crew. Nevertheless, the major barriers of implementing the Last Planner System are linked to the soft aspects, such as people and organization process [7], accordingly, sizing the crew to match assigned work should be taken into account as well. On the other hand, the relationship between reliability, variability and performance is complicated to generalize. There is a need for a comprehensive thinking of assignment and the crew abilities.

1.1. Flow in Lean Construction

Lean construction refers to the application of lean technology to construction industry, and first and foremost, is recognizing and properly identifying the flow to target continuity of work, location and time [7]. The first reason is that the flow combines together planning and scheduling. These two dominators of construction management are associated to a task with the seven conditions [11] (else called resource flow). Secondly, it considers the production systematically rather than transformation.

Since information, materials and equipment are the components of the workflow [16], it requires a smooth movement to avoid the circumstance of continuous changes and congestion on site [13,20]. The unstable movement generates waste, impeding workflow, and obstructing the progress. Hence a smooth workflow means the availability of needed resources and components being smoothly transformed and incorporated into the products or structures throughout the production units (PUs). Unlike manufacturing production, construction crew moves from location to location, which is the third type of flow. Location flow is then expressed as the place where all other flows and tasks are intertwined. Necessarily, the labour flow (distinguishing from workflow), should be considered together with the flow management in the lean construction. It involves the allocation of labour resources to tasks, along with the interaction of labours inside PUs and between PUs.

Previous research [16] has suggested that labour resources needs to be more exposed in a lean thinking. On the other hand, the variability in the construction output (at the crew level) is inevitable, yet it should be minimized.

To sum up, it is obvious to notice that the site production (construction production) influences the nature of production flow and temporary organization establishes inter-organizational interfaces between the tasks. Eventually, construction peculiarities significantly affect the flow reliability, thereupon, it can be derived that effective management of flow has critical importance to improve the reliability and the feasibility of the production system.

1.2. Reliability and variability

Reliability means that a system can consistently perform its intended and required mission. It is the result to which degree the designed system can be relied on. Numerically, it is the outcome to show validity of tested results, determined through statistical methods after repeated numbers of trials [16]. This statistical method is generally adopted in the project management field. For instance, Monte Carlo Simulation technique is utilized to calculate the probability (higher probability equals to greater reliability), which is used as a tool for decision making. Variability refers to a range of possible outcomes of a given situation. In general, this cause can be seen from the result of a complex system, which is inherently less reliable than a simple system. As for production itself, there are two types of variability in flows: 1) process time variability, and 2) flow variability [9], and both of them are related to labour flow [2]. The process-time variability refers to the variability of the time that is required to transform inputs into a finished product at one workstation. Flow variability means the variability of the arrival of jobs from inflow to a single workstation.

Variability increases the lead time based on the queueing theory [11] and wastes capacity [9]. On the other hand, Shewhart [18] realized that variability is a fact of industrial existence that could be understood by probability and statistics theory. Therefore, interpreting information as data set, to calculate range, mean, variance and standard deviation, can assess the flow variability.

1.3. Flexible and available capacity of labour resources

Increasing the flexibility of labour resource is an important strategy to achieve a reliable flow. It allows the ability of operations to react to the variable conditions. Previous research [10] suggests that problem existing in a production system is that the systems do not work well when every worker tries to optimize their performance without understanding how their actions affect the larger web. Therefore, it is important to increase the flexibility of workers' abilities to avoid the changes and uncertainty. Another approach, is by under-loading the PUs to the crew. It indicates that more capacities will be available by doing so [3]. Similarly, one derivate thinking is generated: when the crews are able to do more than one task, buffers [5] can be utilized by reallocating the crews who are flexible. This Crew flexibility means more available capacities in the project.

2. Objective

Workflow has been extensively engaged, yet the labour flow has been paid less attention to, and from all descriptions above, the hypothesis of this research is defined. The objective is to test whether the improvement of labour flow can enhance the flow reliability (plan reliability) and thereby reduce the construction duration. The improvement of labour flow means to reduce the variance of allocation of labour resources to assigned tasks. The results are interpreted by the following aspects:

1. Duration: What is the duration of the project after reallocation of the workforce?
2. Probability: What is the probability that the project can be finished within the duration of critical path?
3. The workload: The realistic number of products produced each day.

3. Methods

To test the hypothesis, three simulations were developed based on the input data, and grouped into two trials which differed in worker's rate.

Trial 1: for 3 simulations, assumed workers rate (quantity of products changes in a relation to quantity of workers) was utilized to correspond to required number of products. It was assumed that the growth of production rate was linear, associated with the number of workers (Fig. 1), which meant that one worker had ability to produce one piece of a product in one working day.

Trial 2, for three simulations, realistic workers rate was defined to investigate the Marginal Product of Labour change. Marginal Product of Labour (MPL) is an economic theory which refers to the change of output (amount of products) by increasing a unit of labour to a process and remaining the inputs of all the other factors unchanged [19]. MPL was calculated as a difference between the Total Product of Labour (TPL) after additional workforce and before. The continuous rise of production rate followed the marginal curve while the number of workers was increasing (Fig. 1). The Total Product of Labour was based on example used in a production sector [1].

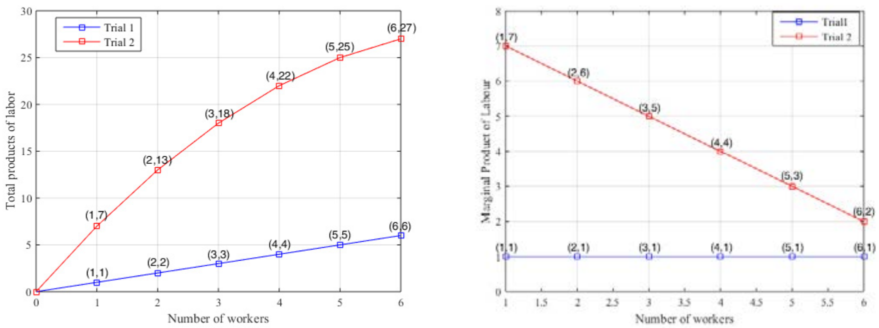

Fig. 1. Total Product of Labour (left) and Marginal Product of Labour (right).

3.1. Input data

Simulations were based on artificial data. The workload for 24 tasks was defined at first (Table 1 and Table 2), and in total 1207-unit products should be completed in a certain time. Due to the complexity of works on a building site, two diverse simplified rates were associated to 24 tasks using numbers 3 and 4 (Table 1 and Table 2). The various task rate in a real case can be found in the example: "*to cast a foundation using pump with a width of 500mm is 0.4 mh/m^2*" and "*to mount a pipe with dimension 100-200mm using concrete pipe is 0.15 mh/r.m.*"

Table 1. Input data: number of products, task rates and workforce for task 1-12.

Task number	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No.12
Products	76	15	48	24	24	54	51	51	20	36	90	60
Task rate	4	3	4	4	4	4	3	3	4	4	4	4
Workforce	19	5	12	6	6	18	17	17	5	12	30	15

Table 2. Input data: number of products, task rates and workforce for task 13-24.

Task number	No. 13	No. 14	No. 15	No. 16	No. 17	No. 18	No. 19	No. 20	No. 21	No. 22	No. 23	No.24
Products	21	44	36	20	144	96	87	28	9	12	9	152
Task rate	3	4	4	4	4	4	3	4	3	4	3	4
Workforce	7	11	12	5	36	24	29	7	3	3	3	38

3.2. Network diagram

The network diagram was developed to show the dependences between 24 tasks of the project. Tasks between nodes are dependent tasks and must be completed in a sequence (Fig. 2). In order to add complex features of construction activities, parallel tasks were designed, and additionally, some activities were designed to have more than one predecessors. The critical path was generated and subsequently the project duration was found.

3.3. Simulations – Trial 1

For all three simulations in trial 1 the following assumptions were conceived:

- External conditions were constant: weather, equipment, safety, etc.
- The minimum capacity of workforce needed for one day was equal to 1.
- Assumed workers rate: One worker could produce one piece of product.
- Total workforce for every activity was fixed (340 workers for all the project).

Firstly, the workload for everyday was different in every simulation, but the total number of workers utilized in each task and the amount of products of each task remained constant. The way to allocate workers to each task was listed below:
Simulation 1: The biggest variance in the workforce. For each task, the number of workers was generated for every working day using uniformly distributed pseudorandom integer from 1 to 6.
Simulation 2: The lowest variance in the workforce. For each task, in order to reduce the variance between the workforce, average number of workers per day was assumed as 3.
Simulation 3: Lower variance in the workforce. For each task, in order to reduce the variance between workforces, daily average number of workers was assumed as 4 and 3 workers.

Secondly, the number of days to finish a task with available workforce was computed by the formula:

$$\text{Precise days}= \frac{\text{Product per task}}{\text{Task rate} \times \text{Average workers per task}} = \frac{\text{Workforce per task}}{\text{Average workers per task}} \quad (1)$$

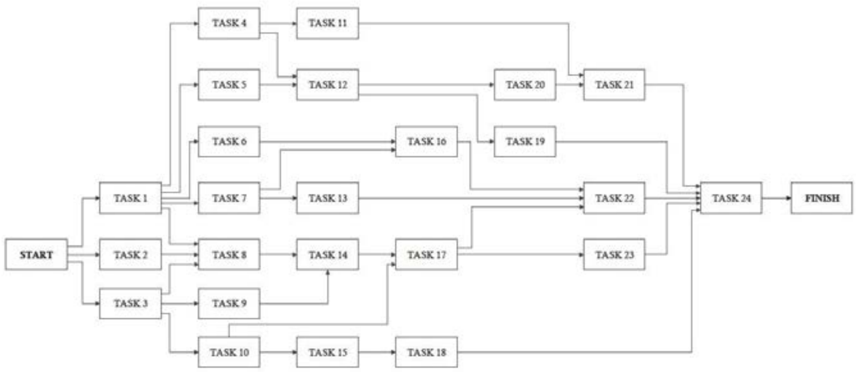

Fig. 2. Network diagram.

It was assumed that when a task takes half a day (when the result of *precise days* is not an integer, rounded number was utilized, and *Half day* refers to reminder that was lower or equal to 0.5), half-day workers are assigned, but to calculate duration of this task, number was rounded up to integer. This duration was assumed as most likely (t_{ml}) and based on that number, optimistic (t_{min}) and pessimistic time (t_{max}) was estimated. The optimistic duration was assumed as 65% of t_{ml} and a pessimistic duration as 210% of t_{ml}. These computed 3-estimat times were utilized as input for Monte Carlo simulation in a later step.

Finally, total amount of workers and total amount of products for each working day were calculated. Standard deviation (σ) was computed in Matlab using one row matrix consisting the workforce for every working day.

3.4. Simulations – Trial 2

The same assumptions and steps were utilized, like described in trial 1. The only difference in trial 2 was the workers rate – *realistic workers rate* was used, unlike in the trial 1- *assumed workers rate*.

3.5. Monte Carlo Simulation

According to the probability theory, a certain probability will approach balance after a quantitative analysis of large sets of data [13]. Using Monte Carlo Simulation (MCS) a task time was computed nine hundred thousand times where a near-critical path was examined [15].

Erlang distribution which is closer to production system was utilized as a function for the simulations. Each activity was computed with the local mean value and standard deviation using the following formulas:

$$m = \frac{t_{min} + (2,9 \times t_{ml}) + t_{max}}{4,9} \tag{2}$$

$$\sigma = \left| \frac{t_{max} - t_{min}}{4,65} \right| \tag{3}$$

Where mean (m) represents medium change for activity to be finished in expected time and standard deviation (σ) is a measure of variability in the total duration.

Duration of the project is calculated by randomly selected probability distributions. The procedure is repeated thousands of times to generate a distribution of the project duration. It gives an “expected time” as a result (which could be different from the original duration of the critical path).

Diverse tasks are distributed in many different ways and according to the Central Limit Theory, a distribution of a project duration is normally distributed. The outputs of MCS are resulted in probability density function (PDF) and corresponding cumulative density function (CDF). Duration of 35 days ("expected time" to finish the project taken from simulation 1) was tested to find out the probability that the project can be completed on time in each simulation.

4. Findings and discussion

4.1. Simulations – Trial 1

The results of three simulations in trial 1 are illustrated in Table 3.

Table 3. Summary for Trial 1.

Simulation number	No. 1	No. 2	No. 3
Assumed products		1207	
Workforce sum		340	
Workforce	7.4	5.9	6.7
Workforce range	[1,6]	[1,3]	[1,4]
Average workforce [workers/day]	9.7	7.9	10.3
Peak workforce [workers/day]	27	20	21
Critical path [days]	35	43	33
Probability to finish the project in less than 35 days [%]	4.2	0.2	10.6
Probability to finish the project in less than 43 days [%]	51.7	6.6	71.6

Observation 1

As the Table 3 shows, simulation 2 had the lowest variance of workforce for each working day ($\sigma = 5.9$) but it had the longest project duration 43 days. However, simulation 3 had the shortest project duration 33 days with the median value of standard deviation which was 6.7. It was the evidence to indicate that reducing variability of workers, did not necessarily decrease the project duration. Based on the assumptions for the simulations, it was found that the bigger number of average workers for each day, the shorter the project duration would be.

Observation 2

For simulation 1, the probability was increased when the expected time became longer (from 35 days to 43 days), the probabilities were 4.2% and 51.7% respectively. For simulation 2 and 3, the probabilities got higher likewise. The results demonstrated, that in a given condition, the probability to finish the project was increasing as the expected days rose.

Observation 3

Simulation 2 was not taken into account in this observation, due to its critical path duration that varied a lot compared to other two simulations.

When the project was not time-constrained project, the demanded days to finish the project were 35, 43 and 33, and the corresponding probability was respectively 4.2%, 6.6% and 4.4%. Linking the value of probability to the value of workforce standard deviation (7.43, 5.87 and 6.72), the results showed that the relationship between these two variables was inversed. On the other hand, these low probabilities (4.2%, 6.6% and 4.4%) stated that the reliability of the plan was inherently low, the critical path of this plan was easy to be affected by other near-critical paths.

When the project was defined as a time-constrained project, 35-day was designed as the requested time to finish it. Difference between data from Simulation 1 and 3 shown a raise of probability in Simulation 3 by 6.4 percentage points. When 43-day was defined as the expected time, the difference in probability significantly increased by 19.9 percentage points, which was 3 times larger than the rise from 35-day duration. When the expected time was given 8 days more, the probability increased considerably. It was suggested that reducing the variability of workforce allocation could help to improve the plan reliability at a large extent.

4.2. Simulations – Trial 2

Total number of products in trial 1 was constant for every simulation (1207). After applying realistic workers rate, the uppermost workload was in the second simulation (7281) and the lowest in the first one (6606) (Fig. 3).

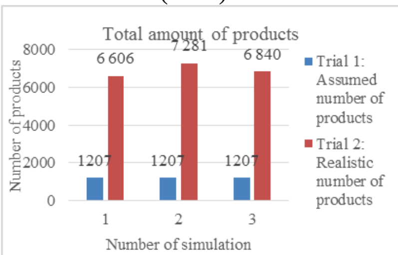

Fig. 3. Total amount of products for trial 1 and 2.

To compare the simulations 1-3 in trial 2, to simulation 1-3 in trial 1, respectively, the amount of products increase was 5 times bigger for simulation 2 (in comparison to trial 1), which was 10% smaller in simulation 1 and 6% lower in simulation 3. The largest output difference was between simulation 1 and 2, therefore the relationship between those two simulations was examined.

Table 4. Products analysis, trial no.2.

Simulation	No. 1	No. 2	No. 3
Average products [products/day]	76	15	48
Average production rate [workforce/day]	4	3	4

Average number of products produced in one day was the lowest in the 2nd simulation, but the production rate was the highest, subsequently, the opposite happened in the 1st simulation. The research findings revealed that that lower variability in labour flow increase productivity. The findings of this research do not, hoverer, examine the project duration change.

5. Conclusion

Plan reliability results from the stability of the seven conditions that affect the performance of the project. In order to have a continuous delivery production system, processing time variability and flow variability must be reduced. The results of this paper indicate that: 1) the processing time is proportional to the assigned amount of workers and 2) optimizing work sequences is limited by the available resources, of which labour force is the key determiner to that. As the workflow and labour flow are two dominators that have impact on each other, both of them should be taken into account in plan design, thereby reducing labour force variability can help reduce the flow variability to a large extent, consequently increase the plan reliability, yet, not necessarily decrease the project duration. Instead of relying on the schedule-push, results of simulations suggested, that acceptable buffers can be utilized to increase the pre-designed project duration (corresponding to the critical path). It is consequently turning out a higher probability to complete the project. In addition, a significant high rise of this probability can be obtained when the variance of workforce is lower.

Results show that the lower the variance of workforce is, the higher probability to finish the project on time can be. Although, the variance reduction does not necessarily decrease the project duration, the plan reliability can be enhanced. While investigating Marginal Product of Labour, it was deducted that increasing workforce and variability can lower productivity output. Additionally, buffers can be utilized to increase the pre-designed project duration, which is in accordance with the duration of the critical path. Consequently, the probability to complete a project will be higher and plan reliability better. Specifically, when adding buffers to the project, the rise of the probability is considerably high when the variance of workforce is lower.

Due to the peculiarities of construction, scheduling is exposed to unpredictable changes and variability. Such instability minimizes the value, increases lead time and serves generating waste, therefore, to improve this lean principles, continuous workflow has to be put into practice. In the construction industry, workflow and labour flow are two dominators that have impact on each other. Both of them need to be taken into consideration while planning, thereby, the flow can be managed effectively and plan can be more credible. While supporting the hypothesis that reduce workforce variability can increase the plan reliability, this study is conducted based on artificial data. To test universality of this assumption, more simulations based on a range of average workers and standard deviation need to be carried out, and additional simulation experiments must be performed based on real-life project due to the complexity of construction network, yet it requires to collect data taxonomically. In order to diagnose the problematic issues in planning and explore how the workforce affects productivity on site, the future research is deemed to concern the relation between lead time removal and workforce variability reduction

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