CHARACTERIZATION OF FLOW IN MULTI STORIED RESIDENTIAL BUILDING CONSTRUCTION

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ABSTRACT

This paper attempts to characterize workflow in construction and thereby to provide a measure for flow at various levels of the construction process. A process based approach is adapted to model flows in construction. Construction of a multi storied residential building super-structure involving identical activities for each floor cycle was selected to observe, document and analyze the characteristics of construction activity flow. The detailed functions and relationships between resources, materials and information for each floor cycle was documented and analyzed for flow characteristics. Queuing theory approach is used for analysis and parameters for quantifying the flow characteristics are proposed. A preliminary model for characterizing flow is formulated. The application of the model for analyzing flow states is discussed.

KEYWORDS

Flow characterization, Lean Construction, process model, cycle time.

INTRODUCTION

One of the fundamental concepts in Lean production is the creation of continuous flow in the system. Identification and elimination of waste is more feasible in systems that have a distinct flow pattern and high levels of repetition. Although flow is more natural in industries like manufacturing, specific interventions such as preassembly, automation etc., were introduced in such industries to further facilitate flow. Typically, construction is considered to be project based, requiring fabrication of a unique product. As a result, modelling construction as a flow-based process is challenging. However, many of the processes in fabrication of the constructed product are repetitive and there is potential to structure construction as a flow based model.

The broad objective of this research study is to explore different types of construction projects and quantify the various types of flow prevalent in the current state. Further, characterization of the flow parameters, flow levels and possible interventions to facilitate flow will also be explored. As a first step, construction of a

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multi storied residential building super-structure, involving identical activities for each floor cycle was selected to observe, document and analyze the characteristics of construction activity flow. The various functions and relationships between resources, materials and information for each floor cycle was documented and analyzed for flow characteristics. Based on the analysis, potential parameters for quantifying flow characteristics are proposed. A preliminary model for characterizing flow on similar projects is suggested using queuing network theory approach. The application of these models for analyzing and improving flow are discussed.

The paper is structured as follows: First, the various approaches to flow in lean manufacturing and in construction are discussed. Second, a model representation of processes in construction is presented. Next, the potential characterization of flow in construction and a flow index model is proposed and its application methodology is discussed. Then, a case study to explore various processes and their interactions is presented. Finally, the limitations and the summary are presented.

FLOW IN LEAN

One of the fundamental objectives in production is to achieve the continuous flow of the product (Womack and Jones 2003). Creating flow in the production system significantly improves the efficiency of the process (Ford assembly line). Creation of flow results in repetitive process cycles which is essential for observations and measurements. This can enable identification of wastes existing in the system, implement and check changes for continuous improvement. Measurement of flow in the current existing state is required to better understand the process conditions and to decide on the improvement steps. Factory physics (Hopp and Spearman 2008) propose models to study flow in manufacturing using queuing theory approach.

The flow based view of construction is proposed by various researchers. Koskela's (2000) TFV theory of production views construction as composed of flow processes and identifies the various flows existing in the system. The theory identifies different types of flows existing in the construction process.

The Last Planner System (LPS) of production control (Ballard 2000) provides a framework for work flow control in construction. Work flow is explained as the movement of work between the teams (production Units) in desired sequence and rate. The look ahead process presented in the LPS facilitates flow of work by series of steps, such as determining appropriate activity sequence and rate, constraint analysis, pulling work from upstream team, matching load and capacity etc. By analysis of various constraints and the reason for non completion of planned assignments in the weekly meetings it improves collaboration and transparency between the teams. The reliability of the look ahead plan is significantly enhanced. Thereby reduces workflow variability and waste forms, like waiting and underutilization of resources.

The Critical Chain Project Management (CCPM) (Goldratt 1997) is another method which addresses the flow of work. It is the development of the Theory of Constraints used in manufacturing to improve workflow. This method primarily aims at reducing project lead times by managing the critical chain and project buffers continuously throughout the project. The frequent and close monitoring of the projected time to complete and buffer utilization enables identification of priorities and decision on appropriate remedial action. In the comparative analysis between the

LPS and CCPM concepts, Koskela et. al (2010) presents that the two systems address different aspects of flow in production and can complement each other.

The idea of Construction Physics (Bertelsen et. al 2007) proposes an understanding of construction process from flow perspective. Various possible models to represent the construction flow are suggested. The idea of 'critical flow' to represent the bottleneck of the process is also presented.

Shingo (1989) states production as a network of processes and operations flows. He distinguishes process as the flow of materials from operations as the flow of men and equipments in time and space. The relevance of this classification in construction is discussed in detail by Kalsaas (2010). A model to measure workflow based on Shingo's operations flow perspective of construction is presented (Kalsaas 2011, 2013).

The current paper, however, adopts a process based approach in line with Shingo's process view as was done by other researchers (Ballard 2000, Bertelsen et. al 2007). Rooke et.al (2007) states that the difference between process and operations depends on the perspective adopted. This study positions the focus on the material or the product that is flowing.

REPRESENTATION OF FLOW IN CONSTRUCTION

The assembly line in a typical production system is characterised by chain of processes that are highly repetitive and continuous. Construction operations also are repeated over and again in various levels. For example, in a multi storied building the structural elements like columns, beams, slab etc are repeated for each floor with almost no variation (at least after certain number of base floors). The presence of repeated identical tasks provides the opportunity to represent and analyse construction like a manufacturing production line. Some of the obvious differences are that the manufactured product moves along series of workstations until completion where as the built product remains stationery and work crew moves around working on it.

In a typical assembly line in manufacturing, the main product flows through the assembly line and the various components gets integrated into the product sequentially along the flow. Production in construction is similar to an assembly line. In this case the main product and many other flows feeding into the making of the main product flows progressively through different activities. The process flow model of this production can be represented as shown in Figure 1. The main process flow is being fed by various sub process flows. If construction of a building is considered as the main process then the various stream of works like formwork, rebar, concrete etc are the sub processes. This model resembles the river model proposed by Bertelsen (2007). The flow in sub process affects the flow levels in the main process according to the level of dependency. The timing of the sub process flow meeting the main process is also significant in the sense that the next sub process cannot join the main process flow until the previous process has integrated into the main flow.

The constructed product goes through each of the sub processes before getting transformed into the final planned product at the end. Each sub process in turn comprises sequence of processes that gradually add components to the product by consuming various resources. The product while going through this sub processes experiences waiting to various extents. The product passes through the lines of sub processes involving processing and waiting. Hence each sub process can be modelled as a queue through which the product passes. The resources that work on the product, like men or equipment, can be the servers servicing the queues. Considering the whole process flow, the product passes through a series of queues before reaching the final stage. This entire network of process flow presents a network of queues through which the product passes through. This flow through the queuing network is represented in Figure 2.

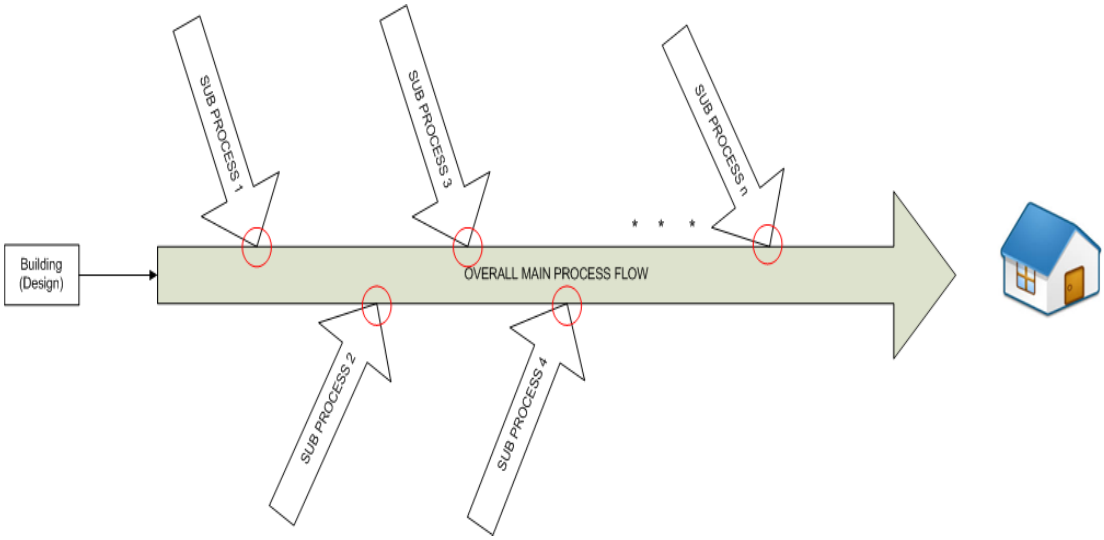

Figure 1: Process flow model

Factory physics (Hopp and Spearman 2008) uses queuing theory to analyze flow in a manufacturing production line. The possibility of studying construction processes using queuing theory is earlier indicated in the concept of Construction physics (Bertelsen et. al, 2006). Factory physics principles can be used to study a single process line to determine various performance measures like Cycle Time, WIP (Chin and Russell 2008, Chin 2009).

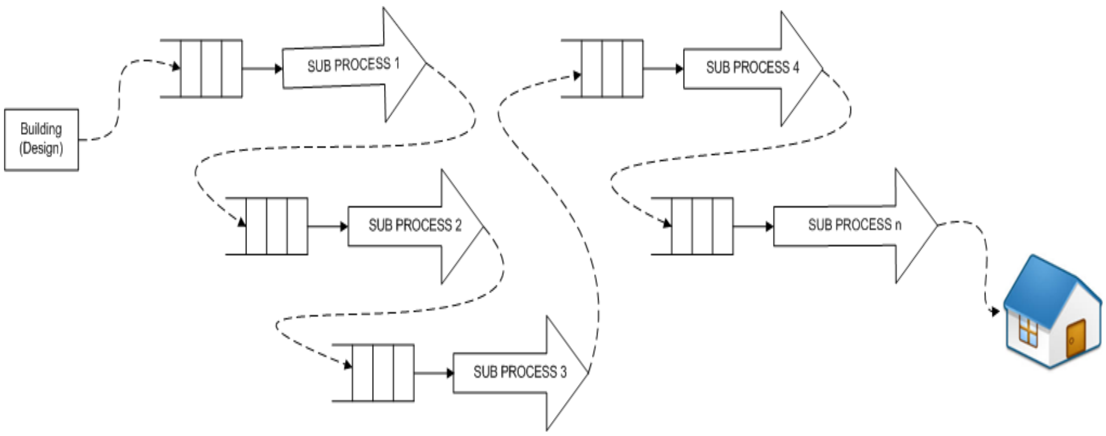

Figure 2: Process Flow Queuing Model

However, to study the entire network of process flow, queuing network models may be used. A queuing network refers to a system comprising several queues with service stations and the entity entering the system gets served at all or some of the service stations. Jackson's open queuing network model (Jackson 1963) can be used to study the behaviour of the network of queues. An open queuing network is a system in which an entity enters and gets serviced in a network of queues and leaves the system after completion of service. Various performance measures like total processing time in the queuing system, utilization of various stations can be obtained.

CHARACTERIZATION OF FLOW IN CONSTRUCTION

This section discusses selection of the factors that can be used to characterize and quantify flow in the process. In a flow based process view, processing is viewed as conversion or transformation aspect of production and inspection, movement and waiting are seen as the flow aspects (Koskela 1992). Kalsaas and Bolviken (2010) presented a basic understanding of the term flow from various disciplines like fluid, traffic, psychology etc. and concluded that flow can be a chain of events with continuous movement and moving freely and adding value.

Time, cost and value are the units by which flow processes can be characterized (Koskela 1992). This report suggests cycle time is an appropriate parameter for the characterization of the flow process. Cycle time in turn is comprised of components like processing time, inspection time, waiting time and moving time. Cycle time provides the measure of the overall process and insights about repeated cycles of the process as a whole. In order to determine the extent of flow within a cycle, a more detailed measure for that cycle will be required.

WAITING TIME

Of the components of the cycle time, the apparent element that affects flow is waiting time. Waiting time is often the largest component of cycle time (Hopp and Spearman 2008). If the product is waiting then there is a clear indication of disruption of flow. One of the fundamental requisite for flow is the product has to move continuously through the various processes without waiting in the process line (Womack and Jones 2003). Hence a process line with no or minimum waiting time[1] can be claimed to exhibit good flow. Waiting time also relates directly to the continuity aspect of flow in terms that absence of waiting time ensures continuity of the flow. Inspection can also be viewed as a form of waiting as the product waits for being cleared after inspection.

Waiting time can be represented with respect to the overall process time in the flow under consideration. A factor termed as Waiting Time Factor is proposed and can be represented as below:

$$\text{Waiting Time Factor, WTF} = \frac{t_w}{t_p} \quad (1)$$

where,

t_w - total waiting time in the process flow

[1] Waiting time of the product in the flow under consideration, for example, in a formwork flow, it is the waiting time of the actual formwork involved.

t_p- total process time of the process flow.

UTILIZATION

The process flow in which there is no waiting of the products but the resources or workstations are not properly utilized or idle, will deliver low throughput. Although the flow in this case is not disrupted, the level of flow is below capacity. Good flow is characterized by combination of high production volumes and uniform production volume per unit time (Kalsaas 2011). In order to achieve high throughput, the resources have to be utilized at an optimum level near to its capacity, contributing directly to the processing time aspect of flow. Thus utilization of the resources can represent the level of flow in the process. Utilization is the fraction of time the resource is in use to the total time and can be denoted as,

Utilization factor (Hopp and Spearman 2008), $\rho = \frac{\lambda}{\mu}$ (2)

where,

λ - rate of arrivals of work in jobs per unit time to the workstation

μ – rate of processing in jobs per unit time of the workstation.

A MEASURE OF FLOW

It is proposed that a Flow Index metric can be utilised to evaluate and benchmark the flow in different states of the system. The flow index developed in this work is based on waiting time factor and utilisation factor. The equation below represents the flow Index metric developed as a part of this study.

Flow Index, $\boldsymbol{FI} = (\mathbf{1} - \boldsymbol{WTF}) \times \boldsymbol{\rho} \times \mathbf{100\%}$ (3)

where, WTF – Waiting Time Factor calculated from equation (1) represents the proportion of time the flow is interrupted in the process. Hence the complementing proportion is considered to represent flow, ρ - utilization factor calculated from equation (2)

APPLICATION METHODOLOGY

The main process flow and the constituting sub-flows are identified by observations of the process for more than one cycle. A detailed Value Stream Map (VSM) is prepared for each sub process flow capturing the process times for the involved processes. The VSM is fine tuned by observing multiple process cycles and the values for the times are simultaneously noted. From this repeated observations, average values for the process times can be obtained. Arrival rate for a sub process is the time between successive beginnings of work for that sub process. Using these two data from the site following measures can be calculated for each sub process and for the whole queuing system.

For the sub process: Assuming *(M/M/1)* queue model, where the arrival time and service time follow exponential distribution,

Utilization, Utilization factor, $\rho = \frac{\lambda}{\mu}$ (4)

Waiting Time in queue = $t_w = \frac{\rho}{1-\rho} t_e$ (5)

For the entire process: In a Jackson open network model (Jackson 1957) following assumptions were made,

a. There are K workstations and the queues are served in First Come First Serve (FCFS) basis.
b. The arrival process to these queues of workstation follows Poisson distribution.
c. The process time is exponentially distributed with mean 1/μ.

Utilization factor for any workstation j is given by, $\rho_j = \frac{\lambda_j}{\mu_j}$ (6)

where, λ_j- arrival rate at station j, μ_j – process rate at station j.

The total time spent by the product in the system is given by,

$$W = \frac{1}{\lambda} \sum_{j=1}^{k} \frac{\rho_j}{1-\rho_j} \quad (7)$$

Where, λ- mean arrival rate in the queuing network.

CASE STUDY

The case selected for the study was construction of multi-storeyed residential building project in India. Each building consists of ground plus 16 floors with two basement floors and there are 33 buildings containing about 2600 apartment units in the project. The entire super structure of the building is made of Reinforced Cement Concrete (RCC). An integrated aluminium formwork is used to cast all the elements of a floor such as the walls, slab, stairs etc., in a single concreting pour and each floor is cast in two concreting pour operations. The formwork flows along with the floor as it progresses. Rebar is cut and bent in a factory and supplied to the site for placement.

FLOOR CYCLES

For the current study, only the casting of RCC structural elements of the floor is considered and other works like finishing are not included. The prime activities of a typical floor cycle involved marking, formwork placement, rebar placement, electrical conduits fixing, services conduits, fixing of outer staging and concreting. After completion of concreting operations, the formwork is removed in the cast floor and moved up to the immediate upper floor for usage. These operations are repeated for both pours. The time taken for one pour cycle averages between 6-8 days. The sequence of operations and their interactions is represented in the diagram in Figure3. This diagram is detailed with having the process flow representation in Figure 1 as the template. The various flows as can be seen from the Figure 3 are Rebar flow, formwork flow, concrete flow and electrical conduit flow. The sub processes are represented in the order of execution. The influence of a sub process on another varies based on the level of dependency between them.

Now let us consider a part of a floor in the building. Each sub process is a queue and the building part gets through this queue of processes in a sub process and joins the queue in the next sub process. The part goes through multiple queues of sub processes in the overall flow until completion. The flow of building through various queues is represented in the queuing view model in Figure 4.

Site data will be collected by observations of the individual sub processes for each pour cycle. Each pour cycle begins when the floor is ready for marking process after concreting and curing and ends with the concreting and curing of the next floor. This will be recorded as the cycle time for each pour. The start and end time for each of the sub processes will be recorded as their process time. In addition to this, the waiting time of the product, the time when it is idle without being worked, will also be recorded. From these observations detailed VSMs are prepared for each of these flows. Arrival time for a sub process will be the time when the previous sub process completes and the product is ready for the current sub process to start work. The inter arrival time and process time for the processes can be calculated from these observations.

In the analysis using queuing model, following are the assumptions that are made. The entity that flows through the queuing process is the actual building itself. The workstation or server can be crew of men or equipment based on the processes. For example, the concreting sub process involves various equipment and crew of men, concrete is made by batching plant, moved near the building by transit mixer, pumped to concreting location by concrete pump, placing by crew of men.

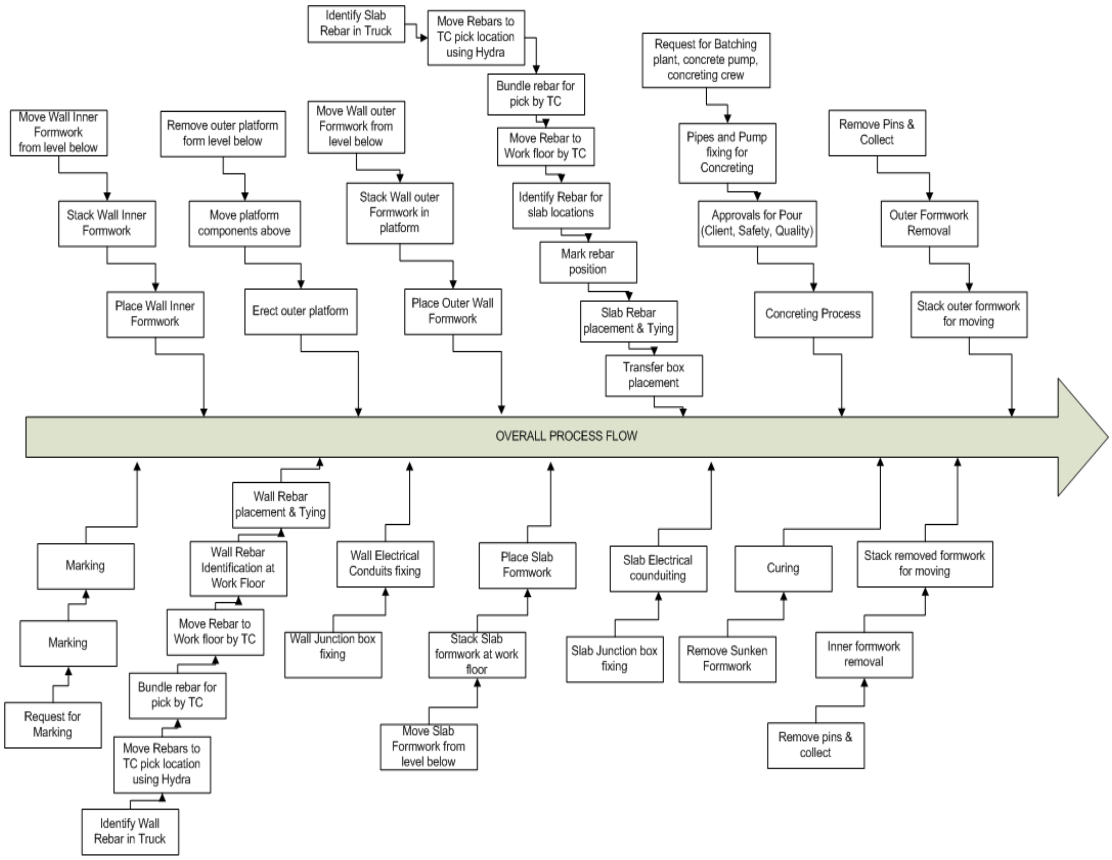

Figure 3: Process flow interaction model

Considering a single sub process, for example marking, using the inter arrival rate and process time from the observations, the utilization of the resource and the waiting time can be calculated using equations (1 & 2). In marking process the resource is a crew of men and hence the calculated utilization is the utilization of the crew. The waiting time calculated is the waiting time experienced by the floor during the marking process. The flow index is calculated using the utilization and waiting time in the equation (3). This flow index represents the state of flow in the marking process. Similarly the flow index for the other sub processes can be calculated. The flow index at the sub process levels provides an indication about the state of flow in the sub process. This can be used to identify problem areas where subsequent detailed causal analysis may be required. Thereby appropriate measures to enhance flow can be implemented.

For the entire network of flow, the arrival rates and process times are calculated for each of the sub processes from the observations. Utilization factor for the sub processes is calculated using the equation (6). The total time spent in the queue is calculated from equation (7) using the mean arrival rate and utilization factor. From this total time the waiting time can be determined by deducting the total process time. The flow index can be calculated from this waiting time and utilization factor.

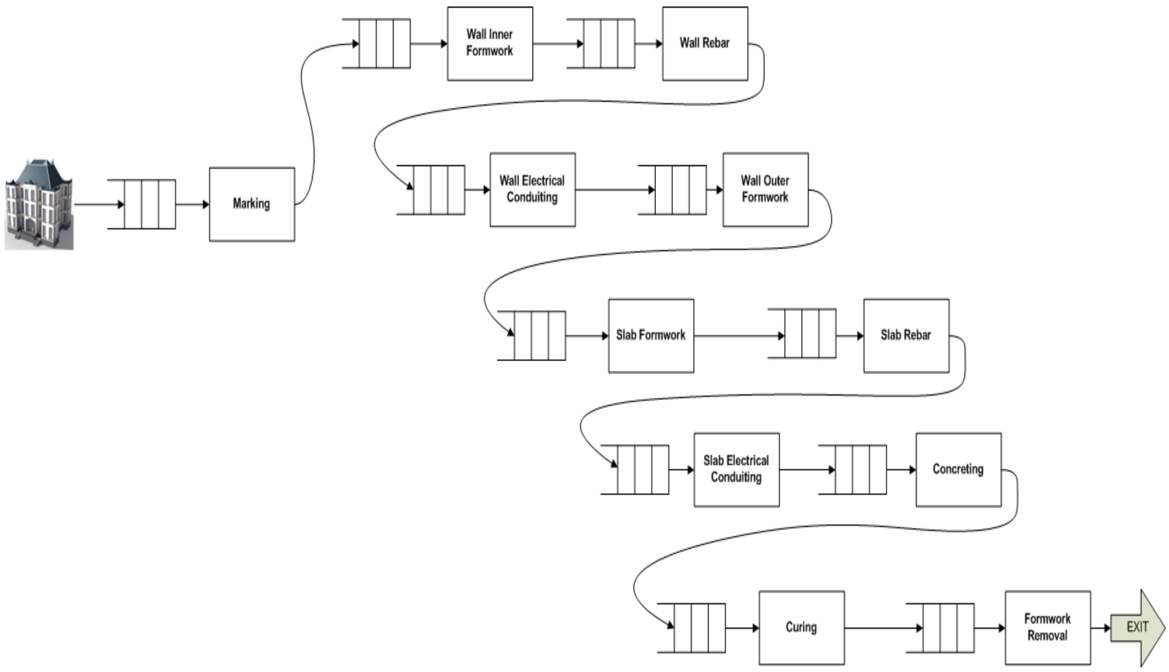

Figure 4: Queuing Model View of Process Flow

The field data for the process times is not available currently for all the processes as the study is on-going. The proposed factors will be calculated and verified in the subsequent stages of work.

LIMITATIONS

The queuing theory approach for analysing the process queue model will be feasible for a simple queue system. When the number of processes is large the model tends to be complex and the approach will be tedious and infeasible. In such cases, tools like discrete event simulation modelling may be used. Second, the factors waiting time of the product and utilization of the resource used for characterization of flow in this study are the potential preliminary factors identified at the current stage. Validation of these factors and the proposed flow index and additional factors that can attribute to the characterization of flow need to be explored. And, the assumptions made for applying the queuing model regarding the arrival times and process times need to be validated with the information collected from the site.

DISCUSSION AND SUMMARY

The paper places the focus on the product or material in the flow under consideration. The model representations in the paper are visualizations of flow from the product perspective. The case study presented is characterized by highly repetitive and large volume production which fits into the Shingo's reference in manufacturing. The process based representation of the construction process presented in this paper describes the flow of the built product through processes at various levels. The dependency between the individual sub processes flows and their influence on the main flow can also be known from the model. The metrics suggested can be the basic parameters to quantify flow. The queuing network model of the flow process seem to be a potential representation of the condition appropriately, and solving the model can result is metrics that can be used to measure flow.

With reference to other flow concepts like the LPS and CCPM, the Queuing model approach can help to identify the flow that affects the overall flow and potential remedial measures similar to the constraint analysis of LPS and critical chain management in CCPM. LPS and CCPM introduces pull into the system by various methods (Koskela et. al 2010). With the information about the utilization levels of the resources, the mechanism of pull can be introduced into the process network. However, the psycho-social issues addressed by both the LPS and CCPM concepts are not directly supported in this approach. With respect to the metrics, the proposed flow index is a function of waiting time and resource utilization. The Percentage Plan Complete (PPC) in LPS provides an indicator of the soundness of the planning process, which aims to reduce waiting time and match the work load to capacity. The CCPM calculates projected time to estimation and buffer utilization.

Validations of the proposed model using detailed observations from the site are to be performed in the future. The implementation feasibility when the number of processes in the projects is huge had to be investigated. Alternate tools such as discrete event simulation will also be considered in future work to represent such systems and evaluate alternate scenarios to determine strategies to enable flow.

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REFERENCES

Ballard, G. (2000). "The Last Planner System of Production Control." Ph.D. Diss., School of Civil Engineering, Univ. of Birmingham, UK.

Bertelsen, S., Koskela, L., Heinrich, G., and Rooke, J. (2006)."Critical Flow – Towards a Construction Flow Theory." *Proceedings IGLC14*, Santiago, Chile.

Bertelsen, S., Henrich, G., Koskela, L., and Rooke, J. (2007). "Construction Physics." *Proceedings IGLC15*, July 18-20, Michigan, USA.

Chin, C. S. and Russell, J. S. (2008). "Improving Performance of Process Flows." *Proceedings IGLC16,* Manchester, UK.

Chin, C. S. (2009). "Queueing theory and process flow performance." *Proceedings IGLC17,* Taipei, Taiwan.

Goldratt, E. (1997). "Critical Chain", North River Press, MA.

Kalsaas, B.T. and Bølviken, T. (2010). "Flow of work in construction – a conceptual discussion." *Proceedings IGLC18,* Haifa, Israel.

Kalsaas, B.T. (2011). "On the Discourse of Measuring Work Flow Efficiency in Construction. A Detailed Work Sampling Method." *Proceedings IGLC19,* Lima, Peru.

Kalsaas, B.T. (2013). "Measuring Waste and Work Flow in Construction" *Proceedings IGLC21,* Fortaleza, Brazil.

Hopp, W. J., and Spearman, M. L. (2008). "Factory Physics", 3rd Edition, Waveland Press, Long Grove, Illinois.

Jackson, J. R. (1957). "Network of Waiting Lines." *Operations Research,* 5(4) 518-521.

Jackson, J. R. (1963). "Jobshop-like Queuing Systems." INFORMS, *Management Science*, 10(1) 131-142.

Koskela, L. (1992). "Application of the new production philosophy to construction." *CIFE Technical Report 72,* Stanford University.

Koskela, L. (2000). "An exploration towards a production theory and its application to construction." VTT publications 408, VTT Building Technology, Technical research centre of Finland.

Koskela, L., Stratton, R., and Koskenvesa, A. (2010). "Last Planner and Critical Chain in Construction Management: Comparative Analysis" *Proceedings IGLC18*, Haifa, Israel.

Rooke, J., Koskela, L., Bertelsen, S. And Henrich, G. (2007). "Centred Flows: A Lean Approach to Decision Making and Organisation." *Proceedings IGLC15,* Michigan, USA.

Shingo, S. (1988). "Non-Stock Production: The Shingo System for Continuous Improvement." Productivity Press, New York, USA.

Womack, J. P., & Jones, D. T. (2003). "Lean Thinking. Banish Waste and Create Wealth in your Corporation." Free Press, New York, USA.