A Methodology for Analysing Productivity in Automated Modular Construction

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Abstract –

Automation is generally assumed to improve project productivity. However, not enough research is done in the area of quantitative methods to evaluate productivity improvements through automation in construction. The aim of this study is to develop a methodology for analyzing productivity of any given automation system for construction. A case study of an automation system developed in-house is used for illustration and validation. This system involves automated connections of column modules and coordinated lifting of the column assembly. A laboratory experiment has been done using this system for constructing column structures using modular blocks. The experimental results are compared with their equivalent manual processes. These studies are conducted using EZStrobe simulations which are calibrated using experimental data. Of the various project performance parameters, only time has been included in this study. The results would throw light on the impact of automation on construction activities on-site.

Keywords –

Construction Automation; Modular Construction; EZStrobe

1 Introduction

Automation in construction industry has generated significant interest in the recent times. In many Asian countries, there is significant housing demand for addressing the growing population. Automated modular construction can potentially address this challenge by improving productivity through savings in time and cost. Even though it is generally understood that automated construction can reduce time and cost of projects, not enough research is done in the area of quantitative methods to evaluate productivity improvements through automation in construction. The general aim of this study is to develop a generic methodology for analysing productivity of any given automation system for construction. More specifically, our focus is on using simulation tools such as EZStrobe in combination with site measurements or laboratory experiments for predicting productivity parameters of different possible processes for a task.

2 Literature Review

Recently, there is renewed interest in performance analysis of construction projects using simulations. Many examples of simulation studies in different types of projects can be found in the literature [1-9]. The use of Discrete Event Simulation (DES) using tools such as EZStrobe is particularly gaining attention. Researches are done on the possibilities of combining Genetic Algorithm multi-objective optimization (GA) and Discrete Event Simulation (DES) using High-Performance Computing (HPC) to address the issues of time and cost in construction projects [10]. Limitations of queue-based DES and proposed a non-que-based DES have been studied [11]; There have been studies on the means of improving productivity of construction operations in New Zealand using EZStrobe simulation tool. These studies focused on improvement in planning using data from bridge launching operation [12]. Researchers have also used EZStrobe to study the productivity management of road construction in Thailand and arrive at optimised construction members with least unit cost [13]. There have also been studies on various simulation software used in construction industry and analysed their strengths and limitations [14]. Studies on Simphony simulation tool, its strengths and applications have also been conducted. The tool handles both discrete event as well as continuous simulations [15]. Some works have been done to develop activity-based cycle diagram for bridge construction process and applied it in simulation using

EZStrobe and studied its effectiveness [16].

Based on a review of recent literature in the area of simulation-based studies, it is very evident that there is hardly any work with regards to automation in modular construction. It is a significant area that requires attention and more research work is needed to answer the question: how much improvement in productivity can be achieved through automation in modular construction. This paper briefly illustrates a methodology for assessing productivity in automated construction.

2.1 Knowledge gap identified in the literature review

1. Various authors have worked in the area of modelling construction operations [17-29]. These works are focussed on certain areas such as earthwork, etc. There is hardly any research focussing on productivity studies of automation in modular construction of building structures [30-32].
2. A methodology that compares the automation of modular construction with manual modular construction and field construction practice has not been done so far.

3 Illustration of a Process-Performance-Assessment Methodology

A "Process-Performance-Assessment" methodology has been developed to achieve the objectives of this study. This involves performing discrete event simulations to calculate the time taken to complete the activities of the process. The productivity is computed by using the basic data related to the duration of completion of relevant activities. The overall construction process consists of a decomposition of tasks. Each task is further broken down into activities and sub-activities. The relationships between the activities are captured in the form of activity-cycle-diagrams (ACDs). The probability distribution of activities at the lowest level in the decomposition hierarchy are defined based on site data or laboratory experiments.

In order to illustrate the applicability of this methodology to a practical construction task, a specific example of column assembly is used here. The time performance of an automated construction scheme described in Figure 1 is evaluated using this methodology. It needs to be mentioned that the overall research involves the study of other parameters such as cost which are excluded in this paper. It is admitted that the cost of the automation unit is important from the point of large scale construction; however, this is outside the scope of this paper.

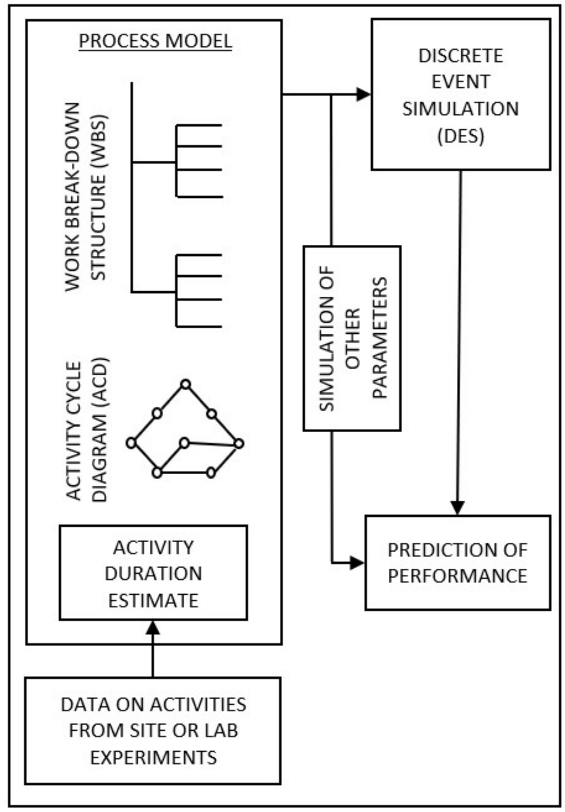

Figure 1. Process-performance-assessment methodology

Previously, an automated scheme using timber modules for the construction of structural frames of buildings has been demonstrated [32]. The idea proposed here is to construct the top floor first and then lift the top part in small steps in order to assemble the modules for lower floors. This will help in performing all the construction activities at the ground floor. This will also support automation since the assembly system can be permanently installed on the ground. The structure is constructed using small timber modules that can be easily assembled. The structural frame of the roof is constructed first. These are lifted using hoists and the columns are inserted below. Both the beams and columns are made of small modules.

The above automation scheme was later adapted for the construction of practical full-scale structures for residential buildings of 1-3 floors. An automated column assembly machine, shown in Figure 2, has been manufactured to illustrate the scheme. As an application example, the process-performance-assessment methodology is used to evaluate this construction scheme. The performance of the scheme is compared with equivalent manual processes in order to bring out the advantages of automation.

Figure 2. Modular column assembly by automation process: bottom to top assembly

Performance assessment involves two stages in this exploratory study:

Stage 1: collection of real time data of three construction processes: a) which is non-modular and non-automated; b) non-automated (manual) and modular; and c) automated and modular.

Stage 2: simulation study of the above three construction processes.

In this exploratory study, a typical column assembly construction is considered. A comparative study of automated process (Case-1) and manual process (Case-2) of modular column assembly; and field-based process of conventional Reinforced Cement Concrete (RCC) column construction (Case-3) is done. Further, simulation-based comparison of all these processes are done. Finally, an assessment of the productivity performance of automation process is analysed and reviewed.

3.1 Description of modular column and RCC Column

The modular column consists of a set of steel modular blocks with a set of connections. In this case, we have eight rectangular modules of dimension 400 (L) x 200(B) x 400(H) mm, as shown in Figure 3. These modules when stacked one above the other and connected will give a total height of 3200 mm. The RCC column is of dimension 300 x 200 x 3200. Reinforcement: 14mm rods 6 no.s; 8mm square hoops@ 100mm c/c and 25mm cover.

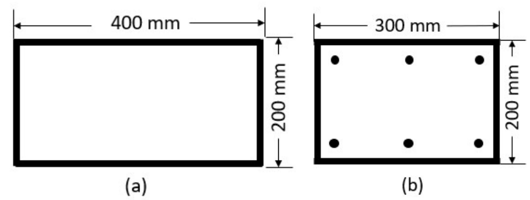

Figure 3. (a) Block module for column assembly and (b) Plan of RCC column

Assumption: It is assumed that the base foundation work is already completed. The column work is extended above the same. In the case of modular assembly, it is assumed that the top base of foundation has connecting component with respect to the first column module block. In the case of RCC construction, it is assumed that the top base of the foundation has extended reinforcement rods which shall be lapped with the column reinforcement during the RCC column execution work. The column reinforcement is already prepared by labour by tying the main rods and stirrups and it only needs to be attached by lapping to the foundation reinforcement. Shuttering is cleaned and oiled. Concrete batch is ready for pouring. Curing is done for 28 days.

4 Exploratory Study based on Laboratory and Field Experiments

The three cases mentioned previously are discussed below.

4.1 Case-1: Modular column assembly by automation process: bottom to top assembly

In Case-1, 8 modules to be assembled are stacked close to the automated assembly machine. Upon starting the machine by a technician, the lifting base would move to its initial position. The technician picks one module at a time, takes it to the machine and places it on the lifting base. The machine lifts up the module till it touches the partially assembled column above and makes the connection between the two using steel pins. Then the new column assembly is temporarily supported by load holding pins and the lifting base is lowered. The process is repeated until all the modules are connected.

4.1.1 Activities of Case-1 as modelled in the simulation tool

1. Start the column assembly process
2. Lifting of block 1: initial position: move to stack: hold one block: lift the block: move to assembly location: place in assembly location
3. Lifting of next block: initial position: move to stack: hold one block: lift the block: move to assembly location: place in assembly location above previous block.
4. Lifting of connector: initial position: move to stack: hold one connector: lift the connector: move to assembly location: place between current and previous block: Connection between blocks
5. Repeat steps 3 and 4 till total number of blocks is 8.
6. Stop the process.

4.1.2 Data collection for Case-1

The process of automated modular column assembly was performed in a laboratory setup in order to estimate the duration of activities involved. The experiment was repeated three times. In a typical experiment, the whole process was completed in 19 minutes and 1 seconds. Time taken for various activities are shown in Table 1.

Table 1. Typical observations of process duration in Case-1

Sl.no.	Process		Sub-activity	Duration (sec.)	TOT. duration (sec.)
1	At Initial Position	a	At Initial position	5	5
2	Lifting of block-1	a	move to stack	10	
		b	hold one block	4	
		c	move to assembly location	10	
		d	place in assembly location	4	
		e	Release the block	4	32
15	Lifting of block-8	a	move to stack	40	
		b	hold one block	4	
		c	move to assembly location	45	
		d	place in assembly location above previous block	4	
		e	Release the block	4	97
17	Back to initial position	a	Back to Initial position	45	45
	TOTAL		IN SECONDS		1146
			IN MINUTES		19.1

4.2 Case-2: Modular column assembly by manual process: bottom to top assembly

In Case-2, two labours are engaged in picking the module and positioning in the assembly location. One labour is positioned at the assembly location while the other moves to and from the stock. The moving labour picks one module at a time, moves to the assembly position and then both the labours place the module in position and check the correctness of positioning. Then the labour moves to take the next module and place it on top of the previous one.

4.2.1 Activities of Case-2 as modelled in the simulation tool

1. Start the column assembly process
2. Lifting of block 1: initial position: move to stack: hold one block: lift the block: move to assembly location: place in assembly location
3. Lifting of block 2: initial position: move to stack: hold one block: lift the block: move to assembly location: place in assembly location above previous block.
4. Lifting of connector-1: initial position: move to stack: hold one connector: lift the connector: move to assembly location: place between current and previous block: Connection between blocks
5. Repeat steps 3 and 4 till total number of blocks is 4.
6. Lifting of next block: initial position: move to stack: hold one block: lift the block: move to assembly location: board on base stool: place in assembly location above previous block: aboard from base stool
7. Lifting of next connector: initial position: move to stack: hold one connector: lift the connector: move to assembly location: board on base stool: place between current and previous block: Connection between blocks: aboard on base stool
8. Repeat steps 6 and 7 till total number of blocks is 8.
9. Stop the process.

4.2.2 Data collection for Case-2

The above procedure was tested in an experimental study and the time taken for each activity was recorded. Since this is only an exploratory study meant for illustration of the methodology, experiments were not repeated multiple times. Time lags were noticed in discussions, decision making, moving between the stock and assembly; positioning; connecting; and boarding and aboarding the base-stool for modules that were positioned above 1.6m. There were also issues of safety due to improper handling of modules during the assembly process. The whole process was completed in 1 hour 51 minutes and 24 seconds.

4.3 Case-3: RCC column construction by manual process

In Case-3, the sequence is Reinforcement placement; Shuttering; Concreting; De-shuttering and Curing. Six labours were engaged- two for reinforcement arrangements; two for shuttering and de-shuttering; and two for curing process. Initially, two labours were engaged in assembling the reinforcement by taking the already prepared reinforcement to be positioned at the RCC column assembly location. The reinforcements were tied by lapping with the rods projecting from the base of footing. Later two labours bring the shutters from the stock and position them at the lower part of the column, provide spacers and fasten the shutter panels. The two labours into concreting prepare the batch and take first batch to fill up to the top of shuttering level. The column is let to set for twenty-four hours and then it is de-shuttered by the two labourers and further positioned up to the next level and the same process is repeated. And finally, the shuttering is extended up to the top of the 3.6m column and concreting process is completed. After the setting and the de-shuttering, the column is cured by wrapping around with wet gunny sacks. The column is sprayed with water at 6 am and 6pm for 28 days starting from day-1 of de-shuttering of first batch casting till day-28 of the curing of the third batch casting.

4.3.1 Activities of Case-3 as modelled in the simulation tool

1. Start the RCC column assembly process
2. Reinforcement placement and tying:
   (a) initial position
   (b) move to stack: hold the rebar: lift the rebar: move to assembly location: place in assembly location: lap with the base rebar: tie with the base rebar
   (c) back to position
3. Shuttering:
   (a) Initial position
   (b) Move to stack: hold shuttering: lift shuttering: move to assembly location: place in assembly location: align in assembly location: fasten the shuttering
   (c) Back to position
4. Concreting:
   (a) Initial position
   (b) Move to concrete batch: hold one portion of concrete: lift the portion of concrete: move to assembly location: position in assembly location: pour the concrete
   (c) Back to position
5. De-shuttering:
   (a) Initial position
   (b) Move to assembly location: align in assembly location: un-fasten the shuttering: hold shuttering: lift shuttering: move to stack
   (c) Back to position
6. Repeat steps 3,4 and 5: twice, each after 24 hours.
7. Curing:
   (a) Initial position
   (b) Move to stock: pick gunny bag: Move to assembly location: Wrap around column
   (c) Move to water pipe source: turn on water: spray on column:
   (d) Move to water pipe source: turn off water: Back to initial position
   (e) Repeat steps c. and e. after 12 hours
   (f) Back to initial position
8. Repeat step-7 c-f till count is 28.
9. Stop the RCC column assembly process

4.3.2 Data collection for Case-3

Observations were done on construction sites in order to estimate the time for basic activities of the above process. Using this data, an estimate of the total time taken was made. The estimated total duration of the RCC column casting process was 31 days 4 hours 15 minutes and 19 seconds.

5 Simulation Study

EZStrobe is a general-purpose domain independent simulation tool that has been widely applied to construction operation studies. It functions primarily based on Activity-Cycle-Diagrams (ACD) and is used for productivity and optimization studies in construction. The process model consists of multiple queues representing activities that are repeated. The present simulation study is conducted for three scenarios namely: (1) process of column construction using modular blocks through automation; (2) process of column construction using modular blocks done manually; and, (3) manual RCC column construction process.

In the EZStrobe simulation model for Case -1, shown in Figure 4, the **Queue element** “Block” is assigned 8 numbers indicating the 8 modular blocks for the column assembly. It is linked to “Load” and releases one modular block at a given cycle. The **Conditional activity element** “Load” is linked to the Queue elements “Block”, “Holder_Idle” and “Move”. “Load” is assigned the duration in the range of 28 to 68. **Queue element** “Holder_Idle” is assigned 1 number indicating that at any given time, the holder of the assembly unit picks one modular unit. It is linked to “Load” in a cyclic loop. The **Bound activity** “Move” is linked to “Load” and “Assemble” as predecessor and successor activities respectively. “Move” is assigned the duration in the range of 20 to 68. “Move” activity functions after the “Block” loads one module to the holder of the automation unit. **Bound activity** “Assemble” is linked to “Move” as predecessor; and “Assembled_units” and “Release” as successor activities respectively. “Assemble” is assigned the duration in the range of 8 and 24. The module, after moving from the stock held by the holder of the automation unit, is placed at the assembly position.

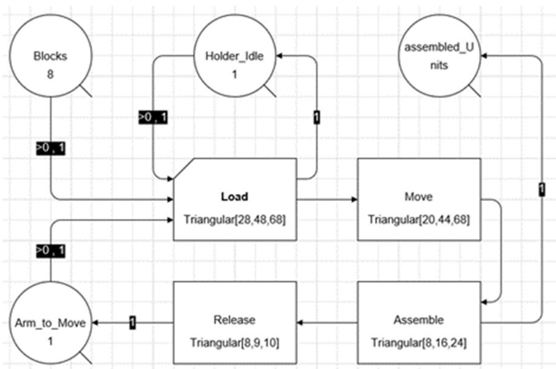

Figure 4. EZStrobe model of workflow for Case-1

Queue element “assembled_units” indicates the number of modular blocks assembled at the column assembly position. The **Bound activity** “Release” is linked to “Assemble” and “Arm_to_move” as predecessor and successor activities respectively. “Release” is assigned the duration in the range of 8 to 10. “Release” activity functions after a module block is assembled in position by the holder of the automation unit. **Queue element** “Arm_to_move” is the moving arm of the automation unit at whose end is the holder. The “arm_to_move” functions the moving between the stock and the assembly location for taking, placing and reverting to stock of modular blocks.

In Figure 5, EZStrobe simulation snapshot of Case-1 is shown. The EZSrtobe simulation controller displays the time taken for simulation with graphical display of stage of simulation. With the option of “Animate” and controlled “Animation Speed” we visualize the sequence of activities taking place. Here, we note the activities between assembling the block and releasing. The “triangular” indicates the minimum, mean and maximum time taken for the activity.

On running the simulation, a report is generated wherein there are series of parameters displayed and numerical values generated after completing the simulation runs. Some of the parameters are time of report, total amount of resource, average content, minimum content, maximum content and so on.

Up on simulation run, the durations of their assembly process are arrived. It is noted that Case-1 has the least duration of 18m 5sec.; Case-2 with the second least time duration of 1h 47m 38 sec., whereas, Case-3 took an execution time of 31d 4h 13m 57 sec. It also closely correlates with the field-based and laboratory measurements.

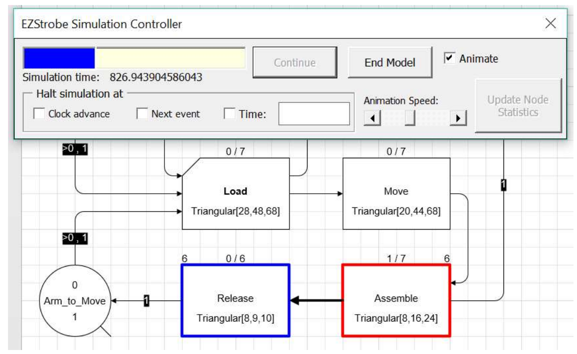

Figure 5. Simulation snapshot for Case-1

6 Comparative Results

The three cases represent three distinct approaches to construct a column and they show significant aspects of the assembly process. In Case-1 (i.e. Modular column assembly by automation process), it is noted that once the automation unit was stationed and positioned, the column assembling using the block is a cyclic process that went without any hindrance, obstacle or technical snag. The time duration taken for each activity and sub-activity is controlled and hence each repetitive activity took the same time duration. In Case-2 (i.e. Modular column assembly by manual process), it is observed that the two-labour executing the process had on and off discussions, deliberations, slowing and speeding up, erroneous assembling, etc. Further, they had to use a base-stool to climb above the height of 1.6m for assembling the modules that added time for work completions. There was also risk of tripping and falling; losing grip of the module from hand. Therefore, safety was also in question in this process. In Case-3 (i.e. RCC column construction by manual process), teams of two performed the tasks of reinforcement placement; shuttering; concreting; de-shuttering; and curing. And thus, this process involved the maximum labour resource. Also, the efficiency and quality of work kept varying throughout the execution. This impacted on the time delays and therefore on the overall productivity of the column construction process. In terms of time duration from these experiments, Case-1 took the shortest, while Case-3 took the longest duration. The simulation analysis further validates this.

7 Summary and Conclusion

This paper illustrated a process-performance-assessment methodology by which the productivity of automated modular construction can be evaluated. A selected automated modular construction process was compared with manual modular construction and equivalent common construction practice at site. A typical case of column construction was studied with modular blocks which were assembled manually as well as through automation. Equivalent study was carried out for an RCC column construction. All these cases were studied through EZStrobe based simulation and analysed. Results indicate that significant savings in construction time can be achieved through automation. Furthermore, the study demonstrates how a process simulation tool can be used to evaluate the overall performance of construction processes.

Future research involves testing the methodology on more complex tasks, collecting more on-site data and refining the methodology. Further research is planned to look into the decomposition of processes which shall lead to the greater degree of understanding on the levels of automation required in the construction process. This methodology also throws light on the positive impact of automation in the productivity of not only the assembly process but on further study shall also do so on the total project performance.

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