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Application of Discrete Event Simulation in Estimating Productivity of Shotcrete Method in Divider Wall Construction

Plamenco, Dean Ashton D.[1*], Germar, Fernando J.[1,2], Caparros, Paolo M.[1]

[1]Institute of Civil Engineering,
University of the Philippines Diliman, Pardo de Tavera St., UP Campus, Diliman, Quezon City, 1101, PHILIPPINES

[2]Building Research Service,
University of the Philippines National Engineering Center, G. Apacible St., UP Campus, Diliman, Quezon City, 1101, PHILIPPINES

*Corresponding Author

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Abstract: Discrete-event simulation (DES) techniques are widely used in modeling complex environments where interaction between time-dependent resources and system processes occur in sequences, such as manufacturing ecosystems or production lifecycles, providing an alternative to traditional work measurement. In this study, labor productivity of using shotcrete process in constructing wall dividers for a simple construction project is estimated using a discrete-event simulation (DES) software incorporating project data on process durations, setup time, and machine mean time to failure (MTTF) as model inputs. The simulated productivity rate of using shotcrete to construct a 1000-sq.m. wall in replications of 200, 500, and 1000 is 1.59 man-hours/sq.m., compared to computed rate of 1.33 man-hours/sq.m. using the Program Evaluation and Review Technique (PERT). The total waiting time with respect to the simulation time considering setup, process-in-waiting, and downtime is 48.9% for a single 8-hour shift per workday arrangement. It is shown that by doing multiple 8-hour shifts the resource utilization of the shotcrete equipment can be improved by an average of 43.8% per additional shift bringing the total waiting time to 9.21% for a continuous 8-hour shifts in a single workday. The methodology aims to provide a better baseline estimate of productivity as it takes in to account historical data as well as waiting time arising from resource limitations.

Keywords: Discrete event simulation, shotcrete, construction productivity

1. Introduction

Shotcrete method is a technique typically used in constructing walls and partitions by spraying the cement slurry to an array of wire mesh guiding the form of wall or the partition. It is conveyed to the surface pneumatically and then carved or troweled to the desired surface finish and form. In the Philippines, the commonly used method in wall construction is brick laying using concrete hollow blocks (CHB). This method is more economical compared to using

*Corresponding author: ddplamenco@up.edu.ph

the shotcrete methodology but is significantly less efficient in terms of work input at an established productivity rate of 2.50 man-hours/sq.m.(Highways, 2007).

The shotcrete methodology, on the other hand, requires significantly less laborers while reducing the amount of time to construct the partition wall. It offers ad-vantages such as reduction of the amount and time for formwork installation and removal, reduced labor costs and construction time duration (Bernardo, Guida et al., 2015). The shotcrete methodology also allows for very flexible logistics and good working safety and environment conditions since the process involves the use of highly standardized assembly and framings.

In order to quantify the input man-hours required by any construction work package, a measurement study is usually done where the work content and standard time is established. Such a study requires hundreds of point observations or samples for a single activity to establish a reliable estimate of the standard time. For complex processes like a construction project, this would translate to thou-sands of point observations to estimate the standard times of each of these work packages in the Work Breakdown Structure. Conducting surveys is another way to establish a baseline estimate of the productivity rate. Although this methodology is limited as this is sensitive to response accuracy and case-specific conditions due to limits on the sample size. With this, the study aims to offer an alternative method of quantifying the productivity rates with a balance of relaxing the sampling requirements while offering a reliable estimation framework by means of discrete event simulation. In this study, the productivity rate of using shotcrete to construct a 1000-sqm wall is simulated using the ARENA Simulation Software. The simulation software is a package primarily used in production systems, while it also finds applications in water distribution and transport networks (Altiok and Melamed, 2010). Given that a construction project is a complex production system with the main product being the building, its inherent parameters can be likened to that of a system of manufacturing processes.

The shotcrete method is broken down into individual processes to obtain process times per work element. A survey among practicing engineers in our case company where the shotcrete methodology is used to construct partition walls was con-ducted to determine the Optimistic, Most Likely, and Pessimistic process times related to each of these work elements. These were then preprocessed to estimate the time averages following (Caparros, 2020). The process times are used as inputs in the simulation modeling which will be further discussed in Section 3.

2. Assumptions and Model Inputs

2.1 Wet-Mix Shotcrete

The research by (Khitab, 2015) involving the different methods and compositions of shotcrete covers the type of method being done in this study. The wet-mix process is discussed thoroughly and is relevant as this is the method used for constructing the divider walls. This process is used mainly for non-structural elements. The wet-mix process used in this study involves using the wet-mix sprayed on to a welded wire mesh setup. The following figure shows the general overview of how on-site job mix mortar is prepared and applied on to a receiving surface.

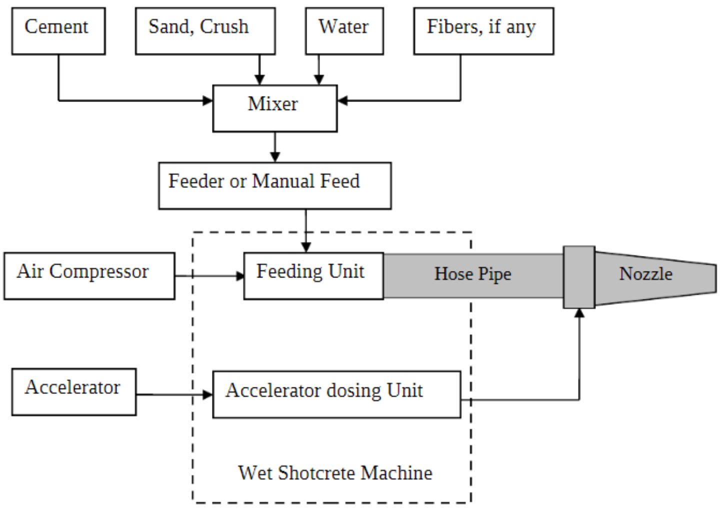

Fig. 1 - Schematic diagram of the wet-mix shotcrete methodology

The shotcrete process that is employed is documented in the following steps:

1. Install 12mm x 100mm wide styropore on the pre-determined center line on columns and beam soffit using a wood glue for seismic gap.

2. Install all applicable plumbed bob tanguile door jambs with 3” common wire nail as spikes and temporary window frames using phenolic boards complete with the necessary bracing and shoring for a guide to avoid misalignment. Upon completion of the shotcreting works, the primary door jamb shall be ready to accept doors and casings. The temporary window frame shall be removed allowing for the installation of the aluminum frames for windows
3. Drill 10mm Ø bar dowels spaced 800mm on center both horizontally and vertically. Insert and cover only the top vertical dowels drilled on the beam by a PVC conduit (16mm Ø x 30cm long). Strap all 12mm Ø vertical bars using Ga 16 tie wire then cover the connection with the PVC conduit.
4. Install the 200mm x 200mm, 3.5mm thick welded wire mesh on one side and the ¼” (fiber mesh) on the other side, making sure that all pre-installed utility conduits are located between the welded wire and chicken wire mesh. All the necessary boxes for utilities should also be pre-installed.

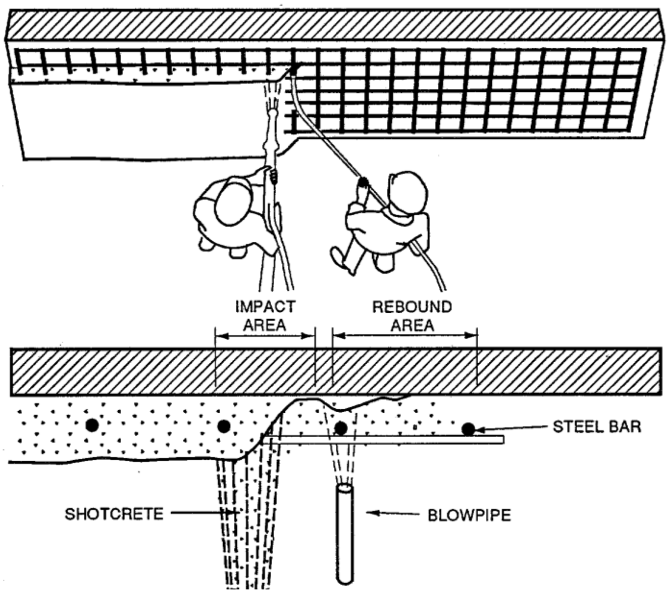

Fig. 2 - Application of shotcrete to the pre-installed wire mesh (After Gideon, 1993)

5. Provide whaler and shoring on the wire mesh for stability. Apply the initial thin cement plaster on the wire mesh. Leave for a day until the cement hardens.
6. Prepare on-site job mix mortar using the defined admixture/additive ratio. Start application of shotcreting works using turbosol machine on the hardened plastered side. Check plumpness, let the concrete bleed and then smoothen using trowel when finished.
7. Remove whaler and shoring then apply shotcreting works on the other un-finished side. Check plumpness, let the concrete bleed and then smoothen using trowel when finished.
8. Using a portable grinder, cut all lines of plastered areas with styropore at 12mm width. Apply a non-sag, paintable structural sealant on 12mm gap
9. Shotcrete wall is ready for application of finish.

The shotcrete methodology to be discretized in the simulation software are de-fined as with the engineers working on shotcrete in our case company and these job modules are identified in Table 1.

2.2 Work Schedule and Crew Size

For the initial model an 8-hour, single shift work schedule is assumed since the case project is not complex and work delivery is not expedited. The typical crew size for shotcreting a 3-m high wall involves 2 bagger mixers, 1 machine feeder, 1 shotcrete equipment operator, 1 shotcrete nozzle guide, and 2 wall finishers. Oftentimes, the shotcrete equipment is placed in the middle area of the room where it can reach the edges for minimum setup requirement. In the optimization model, shifts will be added to determine its effect on productivity and resource utilization. In the model, work breaks were not incorporated as well the down time due to accidents. Consumable resources, such as the input shotcrete mix and wire meshes, are also assumed to be readily available as it is more appropriate to integrate them to construction logistics studies.

Table 1 - Defined job modules related to the shotcrete methodology

Activity ID	Activity
A	Setup Line and Grade
B	Install Styropore on Columns and Beams
C	Drill bar dowels and Install Door Jambs and Windows
D	Place Vertical and Horizontal 12mm bars
E	Placement of Utilities and Wire Mesh on One Side
F	Install Wire Mesh on Other Side
G	Provide Whaler and Shoring
H	Apply Thin Layer of Cement Plaster on Wire Mesh
I	Haul Initial Cement and Sand Bags
J	Place and Setup Shotcrete Machine
K	Prepare Job Mix Mortar
L	Application of Shotcreting Works on One Side
M	Remove Whaler and Shoring
N	Prepare Job Mix Mortar 2
O	Application of Shotcreting Works on Opposite Side
P	Cut All Lines of Plastered Areas with Styropore
Q	Apply Structural Sealant on 12mm Gap

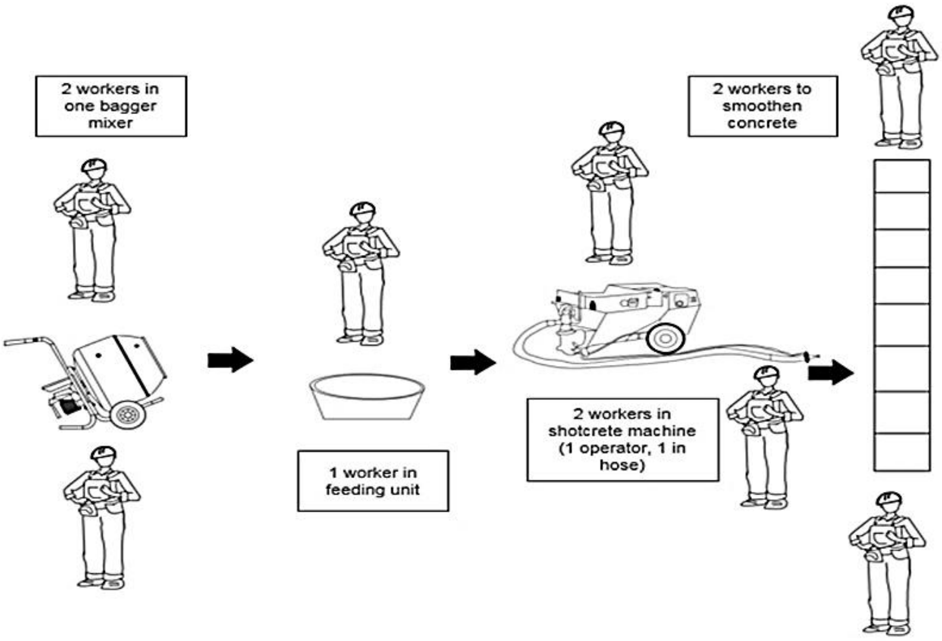

Fig. 3 - Crew assignment

2.3 Resource Model

The simulated project scope is constructing a total of 1000 sq.m. wall interior wall using one (Highways, 2007) shotcrete machine. The mean time to failure of the equipment is assumed to be uniformly distributed between 90 to 180 days. This include ma-chine breakdown and preventive maintenance. The down time is uniformly distributed between 2 to 3 days which involves the ordering of the spare parts required and time to repair.

2.4 Process Times

The process times recorded from the survey and validated by the engineers of our case company are shown in the table below with the following estimates on the means (Bamana, Lehoux et al., 2019).

Table 2 - Process times for shotcrete processes (in hours)

Activity ID	Low	Mid	High	Mean
A	10	8	5	7.83
B	7	5	4	5.17
C	4	3	2	3.00
D	3	2	1.5	2.08
E	8	6	5	6.17
F	4	3	2	3.00
G	3	2	4	2.50
H	2	1	0.5	1.08
I	1.5	1	0.75	1.04
J	1	0.5	0.75	0.63
K	0.75	0.5	0.3	0.51
L	10	7	6	7.33
M	1	0.5	0.3	0.55
N	0.75	0.5	0.3	0.51
O	10	7	6	7.33
P	4	3	2	3.00
Q	3	2	1.5	2.08

3. Simulation Modeling

3.1 Model Generation

With the information on process times and resource requirements, as well as the variability of these data, a simulation model can be generated using the ARENA simulation software. Process times (in hours) are assumed to follow triangular distribution and these parameters were estimated following (Shankar, Rao et al., 2010) using the three time averages (L-M-H). Within the software, time-persistent statistics also record the events happening in a specific process which keep a "timestamp" to the mile-stones related to each these processes. These mark points in time where the processes are started, queued, and finished and when the resource is either idle, busy, or down. The model was also able to account for batching and queueing of tasks, such as when placing the necessary formwork, that is to reflect the model closer to what is happening in the actual project site. The simulation model was iterated in in different sets of replications (50, 100, 500, 1000, and 2000) to determine the reliable estimate. The simulation time is 8 hours a day (single shift) for 365 days. In calculating the productivity of the process the following equation was used:

$$P_{ave} = \frac{VAT + NVAT}{W_{area}} \tag{1}$$

where P_{ave}: Average Productivity (manhours/m²)
VAT: Value-Adding Time (hrs)
NVAT: Non-Value-Adding Time (hrs)
W_{area}: Wall Area (m²)

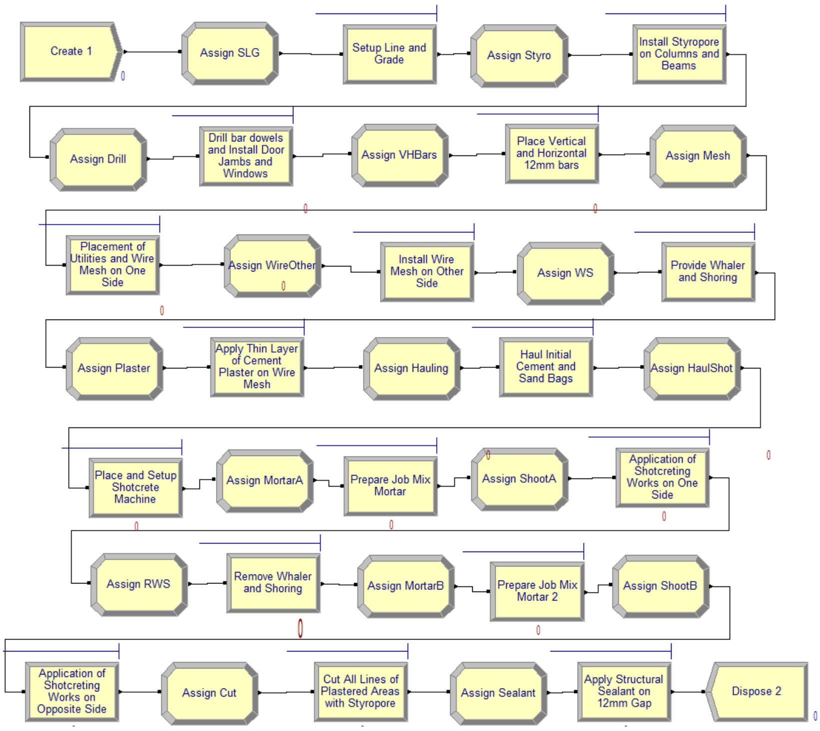

Fig. 1 - Job modules in the ARENA environment

3.2 Simulation Results

The simulation results include the durations due to setup and transport are shown in the table below. The total process durations can be computed by adding the mean simulated duration to the non-value adding time of the process i.e., the time in waiting computed as the number of processes multiplied by the average waiting time.

Table 3 - Simulated value adding time and productivity rates

Iteration	Value-Adding Time (hours)	Productivity Rate (manhours/sq.m.)
20	58.66	1.559
100	58.85	1.562
200	58.92	1.591
500	58.92	1.591
1000	58.92	1.591

In the above summary, the minimum number of iterations required to come up with a reliable estimate is 200. The number of iteration is the number of times the numerical experiments are generated by the software to create simulation data to estimate the parameter of interest. Note that in this case, as you in-crease the number of iterations beyond the optimal number of iteration, the estimate does not further improve. Meanwhile, value adding time (VAT) is the total time elapsed actively processing the entity (wall) thus contributing to the accomplishment of a task. Non-Value Adding Time (NVAT) on the other hand is the total time when the entity is in the queue waiting to be processed due to the resource being unavailable or down and also the time spent waiting for the shotcreting works to dry. The results of the above computation are summarized below in comparison with the simulations done in MS Excel and PERT (Caparros, 2020).

Table 4 - Estimates of productivity rates

Simulation	Productivity (manhours/sq.m.)
Arena	1.591
MS Excel	1.390
PERT	1.333

The duration resulting in the current study is relatively longer than that of the MS EXCEL and PERT Solutions since travel time and setup time are included in ARENA simulations that were neglected (assumed to be zero) in the former calculations. This shows that the ARENA model, as an improvement to the current estimation models, is able to compute the non-value adding time, making it a more reliable productivity estimation tool especially when dealing with projects with limited renewable resources like construction equipment and laborers. It must be noted that it is an assumption of the PERT-CPM that there is no shortage of materials or resource requirements in per-forming the activities thus is a valid lower bound of the estimate.

3.3 Further Simulations

The model is modified by adding another 8-hour shift to maximize the use of the equipment given that the critical process in the methodology is the setup of the mesh framing and the utilities. The intention is to alternate the use of the shotcrete equipment to two different wall systems within its range of mobility - the consequence being is no further setup required. The addition to model is another crew with 7 members, with simulation time of 16 hours per day (double shifts) for 365 days. The number of replications is set to 200.

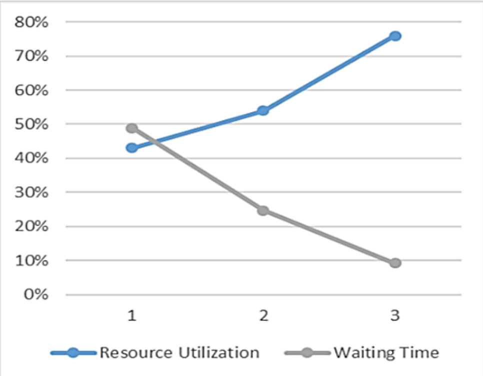

Fig. 5 - Effect of incremental shifts to resource utilization and waiting time

The graphs above show the effect of adding shifts to utilize the shotcrete equipment while there are waiting times due to drying of plaster, setup of meshes, etc. It can be interpreted as different crew members working on another area while there is setup in one area or continuous shifts in a single work-day. The number of times the shotcrete equipment is primed for every wall assembly to be setup is minimized due to continuous use. There is an average reduction of 43.8% per additional shift in terms of waiting time. It is also observed that adding more shifts increases resource utilization which is expected since the methodology is particular in leaving the assembly to dry day-to-day. For, a single shift workday, the shotcrete equipment is left idle due to large setup requirements of the meshing and other support structures. Therefore, using the model, it is shown that we can perform analyses useful as those resulting from work measurements and that we can simulate changes in job schedules and resource availabilities making discrete event simulation a robust approach in measuring productivity rates on the jobsite.

4. Conclusion

The DES Model using ARENA was able to estimate the productivity rate of the shotcrete method and was successful in incorporating setup and travel times that is often neglected in traditional productivity analysis techniques. While it is difficult to have a standard work rate for the shotcrete methodology, there lies the advantage of using discrete event simulation to estimate such rates given the work packages can be broken down to discrete processes. The versatility that the discrete event simulation techniques offer is evident – it requires less effort and it is a reliable way to model the process conditions to determine the productivity rates. At the same time, it offers a way to analyze the effects of changing the work arrangements. In terms of the simulation model, while it is expected the simulation results are site-specific, the quality of the estimation itself can be improved by further establishing baseline reference activity durations per square meter of wall following the specifications set by standard references such as the ACI Reference on shotcrete methodology and by incorporating human factors such as learning curve and rework probabilities in the simulation model.

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