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# Sensitivity Analysis of Construction Processes Using Computer Simulation: A Case Study

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Construction planners and decision makers involved in managing construction processes are always interested in the following issue. The issue is determining the best combination of resources involved in construction processes in a way that maximizes performance measures such as process productivity, total cycle time, etc. Sensitivity analysis is the resolution proposed by planners to settle the issue. In order to do sensitivity analysis, computer simulation provides an inexpensive environment in which all possible combinations of resources can be studied. This paper is aimed at doing sensitivity analysis for resources involved in a construction process to find the best resource combination in terms of process productivity, total cycle time, etc. This was done with the aid of computer simulation that modeled all possible resource combinations in order to predict the outcome associated with each combination. In this study, computer simulation software, Arena 13.9, was employed for constructing the simulation model of a construction process. The results show that the best resource combination improves process productivity and total cycle time by about 6% and 32%, respectively.

**Keywords:** Sensitivity Analysis, Construction Process, Computer Simulation, ARENA 13.9.

## 1. INTRODUCTION

Construction planners and managers are always interested in asking questions about the effects of varying the resources involved in the construction process on the performance measures. They always seek for the combination of resources that maximizes the performance measures such as construction process productivity, total cycle time, total construction cost, etc.[1] The best solution of these issues is sensitivity analysis. Sensitivity analysis evaluates different combinations of construction resources based on their performance measures and selects the best combination that maximizes the measures and satisfies the constraints existed in construction sites.[2] Sensitivity analysis studies the effect of varying the input parameters on the optimum solution.[3]

In order to do sensitivity analysis, computer simulation can be used as an inexpensive tool that provides an environment in which construction planners are allowed to gauge the system response with all possible combinations of resources.[4] Computer simulation is a valuable tool used to model a given real-world operation in order to better understand its nature.[1] It has the advantage of flexibility and low cost over other modeling methodologies such as experimental and mathematical modeling.[4,5] Different alternatives for maximizing performance measures can be simulated and evaluated in a low-cost environment.[6]

This paper addresses how to conduct sensitivity analysis for resources involved in a construction process with the aid of computer simulation. The rest of the paper is organized in 6 parts. First, the application of computer simulation in construction processes is discussed. Second, a case study is introduced for which the sensitivity analysis is intended to be done. Third, data related to different activities of the case study are collected. Fourth, the simulation model of the case study is constructed using Arena 13.9. Fifth, the constructed simulation model is tested to see whether it reflects the real-world process. Finally, sensitivity analysis is done for resources in order to find the best combination of resources that improves performance measures such as process productivity, total cycle time, etc.

## 2. COMPUTER SIMULATION OF CONSTRUCTION PROCESSES

Construction contractors usually perform analysis and design of construction operations intuitively. They determine the number of resources required for a given construction operation based on their experience. It is obvious that this method of determining the number of resources does not lead to the most cost-effective and efficient construction process. Therefore, the process of planning and selecting in a construction process can be challenging. The challenge has caused researchers to seek for a methodology that conducts the process of selecting and

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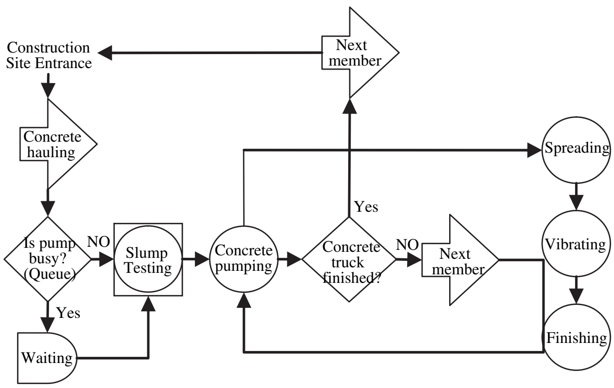


**Fig. 1.** Process map of concrete pouring operation.

planning by predicting the outcomes related to a set of construction performance parameters.[4] Several methodologies have been offered in order to overcome the challenge. Among the offered methodologies, computer simulation provides an environment for decision makers in which they can optimize performance measures and resource allocation and conduct process planning in a low-cost environment.[7] Computer simulation benefits various research areas such as physics, mechanics, management, etc.

Simulation techniques can be applied in a construction process in order to conduct sensitivity analysis. Different combinations of resources can be modeled via simulation software to predict the performance parameters of each combination. This is done in order to find the best combination of resources that improves construction performance parameters. [6]

In this study the simulation software, Arena 13.9, was employed to build the simulation model of a construction process. Arena 13.9 has a powerful graphical interface and consists of template modules that are constructed around SIMAN language.[8]

## 3. CASE STUDY: A CONCRETE POURING OPERATION OF BEAMS AND SLABS

The case study is part of a concrete building construction located in the city of Mashhad, Iran. It consists of two floors and each floor, according to design specifications, needs 420 $m^3$ of concrete to be completed. The concrete operation consists of two main operations. The first one is concrete pouring of slabs and beams and the second is concrete pouring of walls and columns. In this paper, the authors focusing on concrete pouring operation of beams and slabs divided into 4 parts of about 91 $m^3$ of concrete. Concrete trucks that contain 7 $m^3$ of concrete are used for hauling concrete to the construction site.

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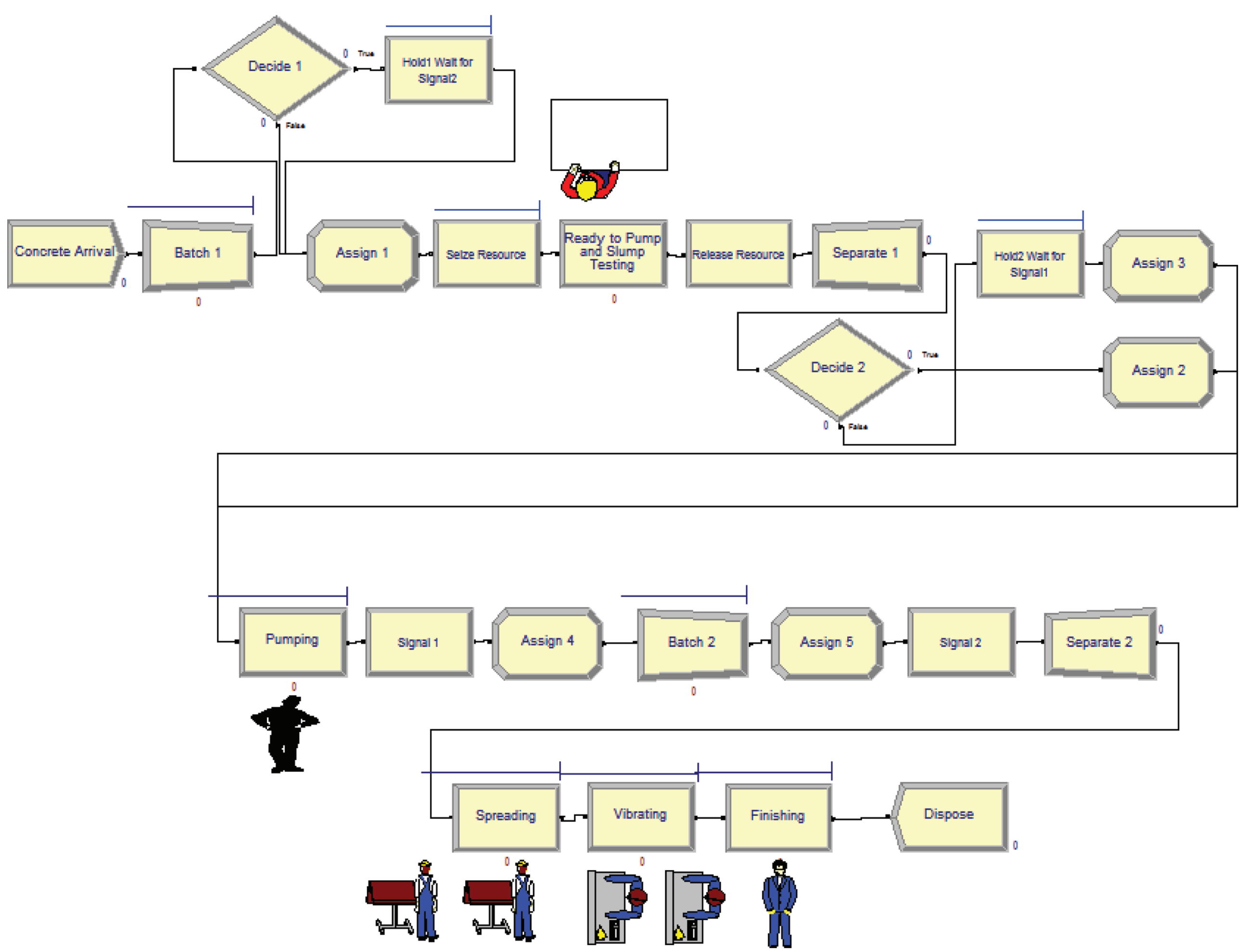


**Fig. 2.** Simulation model of concrete pouring operation built by Arena 13.9.

**Table I. Resource costs and variations.**

| Truck arrival time | Waiting (−) or delay (+) | Ready to pump and slump testing | Pumping (per truck) | Spreading (man · min/truck) | Vibrating (man · min/truck) | Finishing (per truck) | Cycle time[1] | Total cycle time[2] |
|---|---|---|---|---|---|---|---|---|
| 8:00 A.M | 0.0 | 4.5 | 8.5 | 5.0 | 4.5 | 5.0 | 13.0 | 13.0 |
| 8:16 A.M | 3.0 | 3.0 | 6.9 | 6.5 | 6.0 | 5.6 | 9.9 | 12.9 |
| 8:31 A.M | 5.1 | 2.8 | 8.0 | 6.0 | 6.5 | 6.5 | 10.8 | 15.9 |
| 8:46 A.M | 3.7 | 2.5 | 7.8 | 4.5 | 4.6 | 6.7 | 10.3 | 14.0 |
| 9:01 A.M | 5.7 | 2.9 | 6.7 | 6.0 | 5.0 | 7.6 | 9.6 | 15.3 |
| 9:14 A.M | 3.6 | 3.0 | 7.6 | 5.7 | 7.6 | 7.0 | 10.6 | 14.2 |
| 9:32 A.M | 5.2 | 3.4 | 7.0 | 5.0 | 5.6 | 7.8 | 10.4 | 15.6 |
| 9:44 A.M | 1.6 | 3.2 | 7.5 | 6.5 | 7.6 | 8.7 | 10.7 | 12.3 |
| 10:03 A.M | 6.7 | 4.0 | 6.8 | 5.8 | 5.7 | 6.5 | 10.8 | 17.5 |
| 10:17 A.M | 2.2 | 3.0 | 8.1 | 6.5 | 6.5 | 6.0 | 11.1 | 13.3 |
| 10:30 A.M | 1.9 | 2.5 | 7.5 | 5.0 | 4.6 | 8.0 | 10.0 | 11.9 |
| 10:45 A.M | 5.5 | 2.5 | 6.3 | 5.6 | 5.8 | 8.0 | 8.8 | 14.3 |
| 11:03 A.M | 8.0 | 2.8 | 7.8 | 6.0 | 6.7 | 7.5 | 10.6 | 18.6 |
| | After the last truck has left the construction site | | | | 6.0 | 17.0 | 136.6 | **205.8**[3] |

*Note*: All values are in minutes and each value is the average of data collected in field observations. [1]Cycle time is the sum of ready to pump and slump testing and Pumping. [2]Total cycle time is the sum of cycle time and waiting or delay. [3]Total process cycle time is the sum of total cycle times and finishing (After the last truck has left).

## 4. DATA COLLECTION

A simulation model of a construction process needs random durations for each activity. Therefore, having defined the tasks of the construction process, data related to the duration of each task were gathered. For doing data collection, a camera was used to record all tasks. It should be noted that recording was done in a way that did not affect the performance of workers. After recording all tasks, their durations were recorded using a chronometer.

Having collected the activity duration data, a probability distribution was fitted to each data set in order to reflect the randomness of tasks durations. To do this, a statistical computer package named EasyFit was applied. The aforementioned package has many continuous probability distributions that can be fitted to a given collected data set. Examples of such distributions are Exponential, Beta, Gamma, Uniform, etc. EasyFit also performs goodness-of-fit tests (such as Chi-squared, Kolmogorov-Smirnov tests, etc) for all distributions in order to rank them based on the tests results. A simulation modeler can select the most promising distribution according to the ranking.

## 5. MODEL DEVELOPMENT

Having defined the best probability distributions, it is time to build the simulation model of the construction process. The process map, distribution's parameters, and actual behaviors were used to accurately model the conventional concrete pouring operations. Figure 1 displays the process map of the concrete pouring operations in which activities of the process and their sequences and flow of the work were determined based on field observations. Using Arena 13.9, a basic model of the concrete pouring operations was developed, which is shown in Figure 2.

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## 6. MODEL TESTING

Prior to doing sensitivity analysis for resources of the process, the model was tested to ensure that it reflected the real-world process. To do this, first a suitable variable should be selected to show how the simulation outputs and real-world data are alike. The variable selected for model testing in the study is the total cycle time spent on pouring 91 $m^3$ of concrete. After defining the proper variable, the number of model runs to produce adequate outputs should be determined. To do so, the following formula was proposed by Ahmed,[9] considering m initial replications:

$$N(m) = \left(\frac{S(m)t_{m-1,\,(1-\alpha)/2}}{\bar{x}(m)\varepsilon}\right)^2 \tag{1}$$

Where $N(m)$ = number of simulation runs to achieve the desired level of accuracy; $\bar{x}(m)$ = the mean estimate of an initial

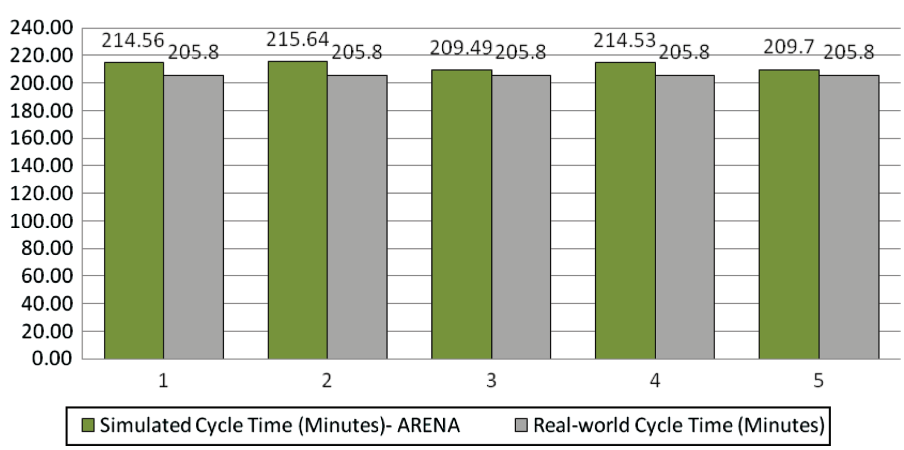


**Fig. 3.** Comparison of simulation outputs with the actual filed measurement.

Table II. Resource costs and variations.

| Name | Cost/hour ($) | Resource variation |
|---|---|---|
| Truck | 25 | 3–5 |
| Spreader crew | 10 | 1–2 |
| Vibrator crew | 12 | 1–2 |
| Finisher crew | 15 | 1–2 |

$m$ number of runs; $S(m) =$ the standard deviation estimate of $m$ number of runs; $\alpha =$ level of confidence; $\varepsilon =$ allowable percentage of error; and $t_{m-1,(1-\alpha)/2} =$ critical value of the two-tailed $t$-distribution at a level of significance, given $m-1$ degrees of freedom.

The mean and standard deviation estimates are determined for an initial 5 number of runs. Then at a level of confidence of 95% and allowable percentage of error of 5%, $t_{4,0.025}$ is equal to 2.776. Inserting the obtained values in Eq. (1) indicates that the number of simulation runs to achieve the desired level of accuracy is 4 replicates or greater. Having defined the adequate number of replications, simulation outputs are compared with real-world data to show how they are alike. It takes averagely 205.8 minutes for a real-world concrete pouring operation to pour 91 $m^3$ of concrete. Table I shows how to calculate the real-world total process cycle time from data collected for pouring 91 $m^3$ of concrete. Figure 3 shows the results of 5 simulation runs compared with the actual output. The average cycle time of the simulation model is 212.78 minutes and the percentage of variation in simulation outputs is 3.39% which is considered acceptable.

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## 7. SENSITIVITY ANALYSIS

This section presents the sensitivity analysis of critical resources of concrete pouring operation. Table II shows critical resources of the process, their cost, and their variation range. Multiple performance measures are considered as decision-making factors in the process of sensitivity analysis. These factors are process productivity, resource cost, and total process cycle time. Process productivity is defined as the ratio of the amount of process output to the amount of input. In other words, it is defined as the amount of concrete poured per unit of cost. Process input is defined in terms of cost. It means that the amount of input is the total cost of the process spent on critical resources. The amount of the process output is also 91 $m^3$ of concrete. Equations (2) to (6) show the calculation of the process productivity in terms of resource costs.

$$\text{Productivity } (m^3/\$) = \frac{91}{\text{Total Resource Cost}} \tag{2}$$

$$\text{Cost of Trucks} = \text{Number of trucks} \times \text{Total cycle time} \times \text{Cost/h} \tag{3}$$

$$\text{Cost of Spreaders} = \text{Number of spreader crews} \times \text{Total cycle time} \times \text{Cost/hrs} \tag{4}$$

$$\text{Cost of Vibrators} = \text{Number of vibrator crews} \times \text{Total cycle time} \times \text{Cost/hrs} \tag{5}$$

$$\text{Cost of Finishers} = \text{Number of finisher crews} \times \text{Total cycle time} \times \text{Cost/hrs} \tag{6}$$

For doing sensitivity analysis, different scenarios related to different resources combinations were defined and modeled in Arena 13.9 in order to predict the process productivity and total process cycle time. Sensitivity analysis was then conducted in order to find the best combination that has the best productivity and process cycle time. Table III shows the results of sensitivity analysis. It should be noted that the first scenario is the one that is currently implemented in real world. Sensitivity analysis pursues a better combination that has the better performance

Table III. Sensitivity analysis results.

| Scenario | Trucks | Spreader crews | Vibrator crews | Finisher crews | Cycle time (hrs) | Productivity ($m^3$/$) | Cycle Time Improvement (%) | Productivity Improvement (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | 4 | 1 | 1 | 1 | 3.546 | 0.1871 | – | – |
| 2 | 4 | 1 | 1 | 2 | 3.463 | 0.1730 | 2.436 | −7.524 |
| 3 | 4 | 1 | 2 | 1 | 3.541 | 0.1725 | 0.180 | −7.794 |
| 4 | 4 | 1 | 2 | 2 | 3.361 | 0.1651 | 5.256 | −11.740 |
| 5 | 4 | 2 | 1 | 1 | 3.522 | 0.1759 | 0.744 | −6.008 |
| 6 | 4 | 2 | 1 | 2 | 3.456 | 0.1623 | 2.436 | −13.232 |
| 7 | 4 | 2 | 2 | 1 | 3.539 | 0.1617 | 0.180 | −13.593 |
| 8 | 4 | 2 | 2 | 2 | 3.375 | 0.1547 | 4.692 | −17.304 |
| 9 | 5 | 1 | 1 | 1 | 3.503 | 0.1605 | 1.308 | −14.224 |
| 10 | 5 | 1 | 1 | 2 | 3.350 | 0.1535 | 5.538 | −17.978 |
| 11 | 5 | 1 | 2 | 1 | 3.523 | 0.1486 | 0.744 | −20.593 |
| 12 | 5 | 1 | 2 | 2 | 2.407 | 0.1998 | 32.044 | 6.775 |
| 13 | 5 | 2 | 1 | 1 | 3.500 | 0.1512 | 1.308 | −19.211 |
| 14 | 5 | 2 | 1 | 2 | 3.327 | 0.1461 | 6.102 | −21.898 |
| 15 | 5 | 2 | 2 | 1 | 3.497 | 0.1413 | 1.308 | −24.480 |
| 16 | 5 | 2 | 2 | 2 | 2.437 | 0.1874 | 31.198 | 0.163 |
| 17 | 3 | 1 | 1 | 1 | 4.470 | 0.1818 | −26.043 | −2.854 |
| 18 | 3 | 1 | 1 | 2 | 4.453 | 0.1610 | −25.479 | −13.943 |
| 19 | 3 | 1 | 2 | 1 | 4.453 | 0.1649 | −25.479 | −11.861 |
| 20 | 3 | 1 | 2 | 2 | 4.340 | 0.1508 | −22.378 | −19.380 |
| 21 | 3 | 2 | 1 | 1 | 4.467 | 0.1669 | −26.043 | −10.817 |
| 22 | 3 | 2 | 1 | 2 | 4.460 | 0.1489 | −25.761 | −20.404 |
| 23 | 3 | 2 | 2 | 1 | 4.453 | 0.1526 | −25.479 | −18.439 |
| 24 | 3 | 2 | 2 | 2 | 4.350 | 0.1404 | −22.660 | −24.963 |

measures. It can be seen from Table III that scenario 12, which is highlighted, is the best resource combination because of the values of productivity and cycle time that are 0.1998 $m^3$/$ and 2.407 hrs, respectively. It can be seen that by executing a simulation experiment for this scenario, process productivity and total process cycle time are improved by 6.81% and 32.14%, respectively. Therefore, the best combination of critical resources for concrete pouring operation is five trucks, one spreader crew, two vibrator crews, and two finisher crews.

## 8. CONCLUSION

This paper attempted to conduct sensitivity analysis for critical resources of the concrete pouring operation of beams and slabs. The concrete pouring operation had four critical resources which were concrete truck, spreader crew, vibrator crew, and finisher crew. The paper focused on finding a resource combination that has better performance measures. In order to conduct sensitivity analysis, computer simulation was applied as an effective and valuable tool. Different combinations of resources were modeled via simulation software, Arena 13.9, to predict the performance parameters of each combination. Results indicated that the best combination of resources were 5 trucks, 1 spreader crew, 2 vibrator crews, and 2 finisher crews. It was also indicated that the aforementioned resource combination improved process productivity and total cycle time by 6.775% and 32.044%, respectively.

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