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Impact of Balance between Productivities on Repetitive Construction Projects

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Abstract

Fast delivery of construction projects provides more value to project owners. Batch production, which is production not in single pieces, but in batches, is a common approach in repetitive construction projects such as multi-unit residential building construction projects. In batch production, the use of a small batch size allows the early start of subsequent activities, and thus can lead to early completion of projects. In addition to batch size, balance between productivities in construction activities can affect project duration. However, the impact of the balance between productivities with regard to their order on project duration has not been studied. The main goal of this study is to test a hypothesis, which is that the order of construction activities' unbalanced productivities affects the amount of time reduction that can be achieved by using a small batch size. A computer-based simulation model was developed, and five different cases were simulated to test the hypothesis. The conclusion of the simulation result is that the order of productivities does not affect the time reduction achieved by using a small batch size. It is expected that the findings of this study can help general contractors make decisions in terms of batch size.

Keywords : batch size, productivity, order in productivities, repetitive construction projects

1. Introduction

Repetitive construction projects are composed of multiple activities that are typically performed by separate subcontractors (or specialty contractors). Also, repetitive construction projects include multiple units (or locations) to be constructed, and each contractor is required to build his/her work in multiple units (or locations)[1]. Work completed by one subcontractor is released to the next subcontractor in a batch (rather than a single piece)[2].

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Since the earlier completion of construction projects provides more benefit to project owners[3,4], careful batch production planning for early completion has been an area of interest for several practitioners and researchers. Batch size is one of the key factors for batch production in repetitive construction projects. It has been reported that the use of a small batch size can reduce the duration of construction projects[5,6,7].

In addition to batch size, productivity in a construction activity affects the duration of construction projects. The balance between productivities in construction activities affects the progress of the overall project[8,9], and also affects the time reduction that can be achieved by using a small batch size[10].

One of the questions regarding the impact of the balance between productivities on the amount of the time reduction that can be obtained by using a small batch size is whether the benefit of a small batch size is affected by the order of productivities. While the sequence of activities in construction projects is not typically changeable, productivity in each activity may be changed depending on other factors such as job site conditions or the amount of resources available[11, 12]. When subcontractors' productivities are well balanced (similar to) each other, operations by multiple subcontractors can be performed smoothly [13]. However, if subcontractors' productivities are not balanced with each other, some subcontractors may need to wait for work completed by an upstream subcontractor, and thus the overall project duration is increased[8]. Project managers in repetitive projects may want to change productivities of activities to reduce duration. Furthermore, project managers may want to know which activity requires an increase in productivity. This means that the order of activities with unbalanced productivities may affect the time reduction that can be achieved by using a small batch size, and understanding this impact can help project managers plan/manage productivities and batch sizes. Therefore, the aim of this study is to examine the impact of order in productivities on amount of time reduction achieved through a small batch size.

This study starts with an introduction to batch production in construction projects and WIP (Work-in-Progress) inventory, followed by the benefits of a small batch size. Also, the impact of the balance between productivities on time is discussed, along with a review of the literature. Then, the research problem and related hypothesis are presented. Next, the computer-based simulation model is introduced, followed by the results from the simulation. Finally, conclusions are presented based upon the findings of this study.

2. Background

2.1 Batch production and WIP inventory

In the manufacturing industry, batch production involves making a type of product with one work station setup. Then, the work station setup is changed to make another type of product. This means, products are made in lots, rather than by piece, with one setup of work stations, to reduce setup costs.

In the construction industry, some construction processes are considered as batch production[2]. For example, a multi-unit apartment construction project is assumed to have ten units on each floor and to be five stories high, as illustrated in Figure 1.

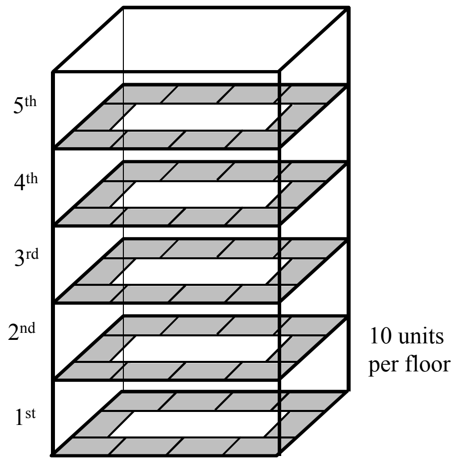


Figure 1. Example of a multi-unit residential project

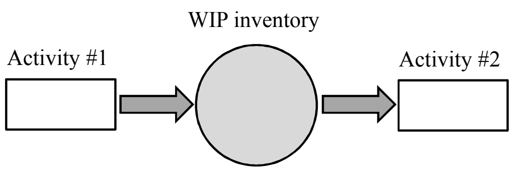


Figure 2. WIP inventory between two activities

If multiple subcontractors (or specialty contractors) are to perform their jobs in each unit, subcontractors need to repeat their processes in multiple units.

The assumption is that each subcontractor occupies all the units (10 units) on one floor, performs his/her job, then moves to the next floor, releasing the floor to the next subcontractor once his/her work on the 10 units is finished. In this case, work finished by the subcontractor is not released to the next subcontractor by unit, but all the units on each floor (10 units) are batched and are only released to the next subcontractor once all 10 units are finished.

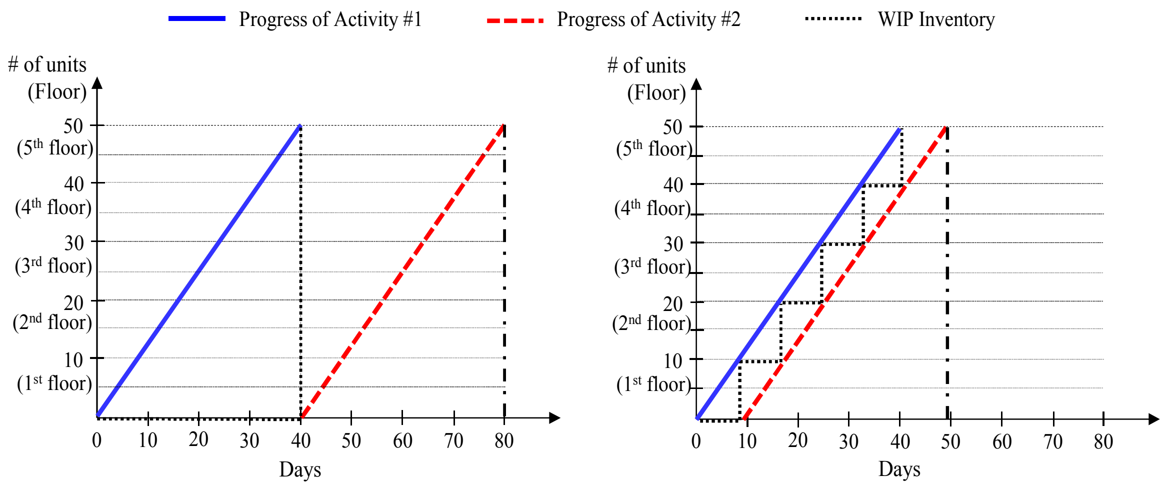
Batch production in construction projects can be observed in repetitive construction projects such as multi-unit residential projects, and in high-rise office building projects. Batch production in construction processes is illustrated in Figure 2.

Between the two activities, there is a Work-In-Progress (WIP, hereafter) inventory, and work finished in an upstream activity is stored in the inventory temporarily before release. Since Activity #2 in Figure 2 requires the work finished by Activity #1 (prerequisite), the amount of WIP inventory may affect the productivity of Activity #2: if there is insufficient inventory, Activity #2 may have idle resources and experience lowered productivity. Thus, the amount of WIP inventory can function as a buffer to protect the productivity of a subsequent activity[6,8,13].

2.2 Batch size and project performance

The amount of WIP inventory means the amount of work that has been finished by a preceding subcontractor and is available, and is affected by how often inventory is released, or batch size. SmallA small batch size allows for the frequent release of work to a nextsubsequent subcontractor, thus facilitatesfacilitating the early start of follow-ing activities. On the other hand, a big batch size requires more time to release the finished work to a nextsubsequent subcontractor. Therefore, batch size has been of interest to several researchers and construction practitioners[5,7,14].

One of the benefits of small batch size is reduced cycle time through the early start of downstream activity, which can lead to the early completion of a project. Another benefit of small batch size is the early detection of defective work. Sawhney et al.[15] concluded that erroneous work could be discovered by the early release of finished work, because subcontractors inspect work released



(a) Batch size of 50 units (on 5 floors) (b) Batch size of 10 units (on each floor)

Figure 3. Comparison between finish times of two different batch sizes

from a preceding activity before starting their own processes.

Figure 3 shows an illustration of two different batch sizes in the example used in Figure 1 and the resulting completion times. Figure 3-(a) is for a batch size of 100% (or 50 units) and Figure 3-(b) is for a batch size of 10 units (each floor). A small batch size allows for the fast release of work completed in the upstream activity, and the step-wise lines (dotted) represent WIP inventory available to Activity #2. In this illustrative example, project duration is reduced from 80 days to 50 days.

Based on the benefits of small batch size, it is recommended to use small batch size in repetitive construction projects, if duration is to be reduced. Also, Ward and McElwee[14] discussed the application of small batch size in construction projects.

2.3 Previous Research on Scheduling for Repetitive Construction Projects

Planning/scheduling for repetitive construction projects has been an area of interest to many practitioners and researchers, and different methods have been proposed (for example[16,17,18,19,20,21]). The scheduling methods proposed, such as repetitive scheduling method (RSM[16]), linear scheduling method[17], and location-based scheduling[19], are focused on the work continuity of each activity (or subcontractor) or the continuity of resources.

In scheduling repetitive construction projects, multiple units are regarded as 'multiples' of each unit, not as a batch of 'multiple units' [16,17,18,19]. Ryu[21] used 'Lead Time (LT)' and 'Lead Space (LS)' to determine the work relationship between different activities. 'Lead Space' is defined as a buffer for work space in a preceding activity, and 'Lead Time' is time required to secure 'Lead Space' of a preceding activity and to procure and allocate resources for the following activity. Both 'Lead Space' and 'Lead Time' are dependent variables, which are calculated based on other variables such as the finish time of a preceding activity, the start time of a following activity, and the cycle time of a following activity. Also, Lee et al.[20] needed 'Lead Space' and 'Lead Time' for activities to determine the shortest duration. 'Lead Space' (and the related 'Lead Time') is similar to batch size, in that both represent multiple units occupied by a subcontractor. However, 'Lead Space' and 'Lead Time' were not regarded as independent decision-variables, but as dependent variables.

2.4 Balance of productivities

Batch size is one of the factors affecting project performance, particularly in relation to time. A construction project's duration can be reduced by having a small batch size, as this facilitates the early release of finished work into a subsequent activity.

In addition to batch size, productivities or balance between productivities of subcontractors is another factor which affects project performance. Tommelein et al.[8] discussed based on the result of the Parade game that balanced productivities among subcontractors whose jobs are consecutive could improve project performance. Compatibility between productivities controls how fast completed work is stored in WIP inventory and how fast completed work is to be used by a subsequent activity.

Both batch size and balance between productivities are important factors affecting project performance. However, there has been little research on the relationship or the interaction between batch size and balance of productivities. Shim[22] experimented with a simulation model of the relationship between productivity balance and work methods. Also, it is found that more balanced productivities between construction activities can enhance project performance[9]. However, no research on batch size and the balance between productivities has been performed.

3. Research problem

It is recommended to use balanced productivities for better project performance. However, it may not be realistically possible to balance the productivities of construction activities performed by separate subcontractors. The productivity of an activity is affected by several factors, such as size of work to do, size of crew, condition of job site and so on. Therefore, changing productivity to achieve balanced progress with other activities may require changes in resource amounts, and changes in other factors. Thus, a change in productivity is related to a change in cost, and subcontractors may be reluctant to pursue higher productivity when an additional cost is required[11].

This study is motivated by the question: what happens to the benefit of using small batch size, if productivities between activities are not balanced. Thus, this study seeks to determine how the benefit of small batch size is changed by different combinations of unbalanced productivities. The focus in this study is on order of productivities: 1) high productivity upstream and low productivity downstream and 2) low productivity upstream and high productivity downstream.

High productivity upstream and low productivity downstream may lead to an increased amount of WIP, and thus a small batch size can allow an early start of downstream activity. Accordingly, the duration of a construction project can be reduced. On the other hand, a combination of low productivity upstream and high productivity downstream may lead to an insufficient amount of WIP inventory, and thus the benefit of small batch size cannot be achieved. Based on this reasoning, the following hypothesis testing can be conducted.

- Null hypothesis (H_0): order of construction activities' unbalanced productivities affects the amount of time reduction that can be achieved through the use of a small batch size.
- Alternative hypothesis (H_1): order of construction activities' unbalanced productivities does not affect the amount of time reduction that can be achieved through the use of a small batch size.

4. Method

4.1 Computer-based simulation model

The model for testing the hypothesis simulates the work flow of construction processes between two activities: upstream activity and downstream activity. Figure 4 shows the composition of the simulation model.

In the simulation model, construction processes are simulated by the flow of work units in different steps: base work (*WB*), work in quality assurance (*QA*), WIP inventory (*Batch*) and work released to and available by a downstream activity (*Finished Work*). *WB* represents work to be done. *QA* represents work under inspection after the base work is done. *QA* is included to represent uncertainty in quality and the rework simulation mode developed by Shim[10] is adopted in the simulation model for this study.

Work units completed from *WB* are determined to be defective or to be non-defective based on the error rate. Defects are detected or not detected based on the error finding rate. If defective work is discovered, the work unit should be redone in *Rework Queue*. Then, work units are transferred

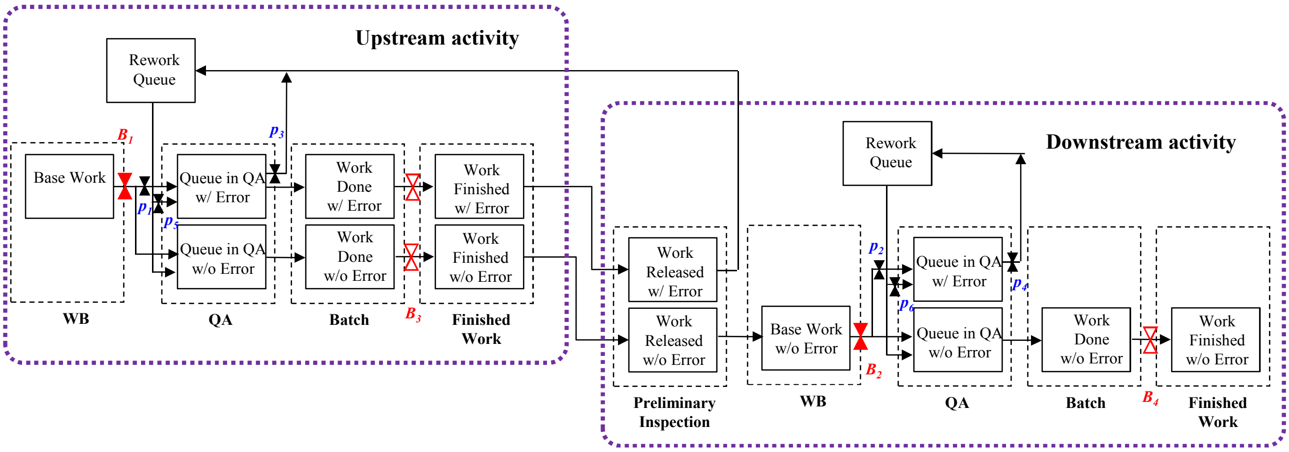


Figure 4. Simulation model

to WIP inventory in *Batch*. It is possible that work in *Batch* includes defects even after the *QA* process. Work units in *Batch* become available to a subsequent activity depending on batch size. *Finished Work* is moved according to batch size. In the downstream activity, the work units from the upstream activity are inspected in *Preliminary Inspection*. And all the faulty work is detected and moved back to the *Rework Queue*.

All the work units of the activities are to transfer from one step to the next in each day (for example, *WB* to *QA*, or *Batch* to *Finished Work*). *Base work* productivity (transfer rate of work units from *WB* to *QA*) is an independent variable in the simulation model and is shown as B_1 in Figure 4. Another independent variable is batch size (B_2), which controls the transfer rate of work units from *Batch* to *Finished Work*. Transfer rates of work units in other steps are assumed to be unlimited: for example, all the work units in *QA* are transferred to a next step (either *Batch* or *Rework Queue*) in the next day. Therefore, all the work units are to move from *WB* in the upstream activity to *Finished Work* in the downstream activity, and completion time is measured.

In addition to the independent variables (productivity and batch size), uncertainty in quality is reflected by including random values which are generated by the following input values.

- Error rate in *Base Work* (P_1 and P_2) determines if work finished in *WB* includes defects or not. The input value for the rates is 5%.
- Error detection rate in *QA* (P_3 and P_4) determines if defects are discovered or not. Error detection rate in the upstream activity (P_3) is 90% and in the downstream activity (P_4) is set as 100%.
- Error rate in *Rework* (P_5 and P_6) determines if reworked work units in Rework Queue include defects or not. The rates are set as 2%.

The simulation model was developed using FORTRAN language and run by Compaq Visual Fortran (ver. 6.6).

4.2 Cases for the hypothesis testing

The hypothesis is set to test the relationship between balance of productivities and the benefit of small batch sizes (time reduction). Therefore, the simulation model is used to examine the

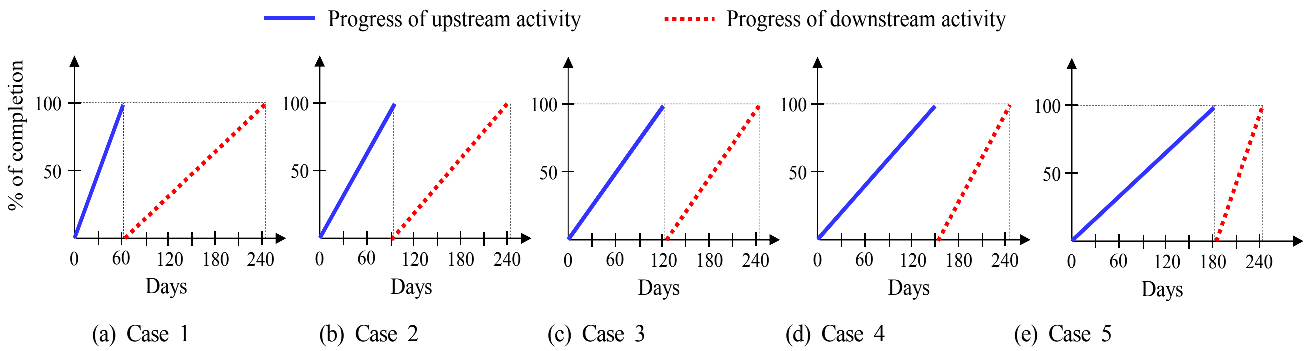


Figure 5. Comparison of productivities

impacts of balance between productivities on time reduction with five cases as follows.

As shown in Figure 5, the five cases have different pairs of productivities. For example, Case 1 and 5 represent the least-balanced productivities. While Case 1 includes a higher productivity upstream and a lower productivity downstream, Case 5 includes a lower productivity upstream and a higher productivity downstream. Case 2 and 4 represent less-balanced productivities and Case 3 represents well-balanced productivities. These different combinations are selected for easier comparison: total expected duration is 245 days for all five cases.

Uncertainty in production rate as well as uncertainty in quality is considered in the simulation model. To reflect the uncertainty in production rates, random values for productivity are generated based on the assumption that productivities are normally distributed. Also, it is assumed that the standard deviation value of productivity distribution is 3 for all five cases. Table 1 shows the mean values of productivities for the cases.

Since it takes 4 days for each work unit to move from *WB* to *Finished Work* in the model, as shown in Figure 4, expected completion time without consideration of uncertainty would be 245 days. Quantity of work is set as 1,800 units, both for upstream activity and downstream activity.

Table 1. Productivities for the five cases

Case	Productivity (Mean value, units/day)		Standard deviation of productivity
	Upstream	Downstream	
1	30	10	3
2	20	12	3
3	15	15	3
4	12	20	3
5	10	30	3

As shown in Figure 5, the five cases have different pairs of productivities. For example, Case 1 is for a higher productivity upstream and a lower productivity downstream, and Case 2 is for a high productivity upstream and low productivity downstream. Case 3 represents well-balanced productivities. Case 2 and 4 represent less-balanced productivities, and Cases 1 and 5 represent least-balanced productivities. These different combinations are selected for ease of comparison: total expected duration is 245 days for all five cases. The expected times of both the upstream activity and the downstream activity are shown in Table 2.

Table 2. Expected durations

Case	Expected duration (days)		Total duration (days)
	Upstream	Downstream	
1	62	183	245
2	92	153	245
3	122	123	245
4	152	93	245
5	182	63	245

To determine the change in the benefit of small batch size resulting from the balance between productivities, the simulation includes five different values of batch size: 100%, 50%, 25%, 20% and 10%. While batch sizes for subcontractors may be different from each other or synchronized (matching batch sizes to multiples of the smallest subcontractor batch[15]), it is assumed that batch sizes for the upstream activity and the downstream activity are the same.

Therefore, the model is to be simulated for 25 different scenarios, which are derived from 5 different pairs of productivities and 5 different batch sizes. The model is run using the Monte Carlo method with random values regarding productivities and uncertainty in quality. The simulation is repeated 20,000 times for each scenario, and completion time is measured in each simulation. Then, completion times of different scenarios are compared for the hypothesis test.

4.3 Model validation

The simulation model was tested in several ways for validation. One of the model validation processes relates to rounding error caused in the generation of random values for productivities.

For this test, error rates for base-work were input as zero, and batch sizes for both activities were set as zero also to reduce the impacts of rework cycle and small batch size. While it was expected that there would be no difference in completion times among the five cases, small differences for mean and variance values were observed, as shown in Figure 6.

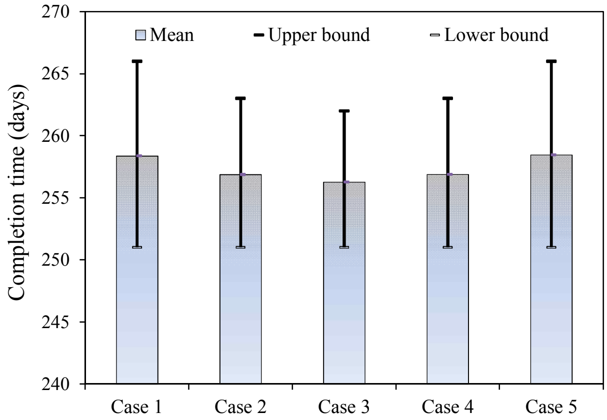


Figure 6. Completion times for batch size of 100% and no defective work

This difference was determined to be caused by rounding errors in generating random productivities. Random productivity values are determined as an integer after rounding down of a random real number based on the given mean value and standard deviation of productivity. When the mean value of productivity of an activity is low, the activity needs more generation of random numbers. Thus, as the mean value of productivity in an activity decreases, the activity is subject to more rounding error. In both Case 1 and Case 5, one of the activities is set to have a productivity of 10 units per day (mean value), which is the lowest value. Thus, both Case 1 and Case 5 are most affected by rounding error. Also, in Case 2 and Case 4, one of the activities has a mean productivity of 12 units per day, and thus these two cases are also subject to rounding errors. However, in Case 3, the productivities for the activities are set as 15 units per day, and the impact of rounding error is observed to be the smallest, as shown in Figure 6. The impact of rounding error in the model is considered for a comparison of the simu-lation results in different cases. The upper bound and lower bound are based on a confidence level of 95%.

5. Results

5.1 Benefit of small batch size

Figure 7 shows completion times with a batch size of 100% and error rate of 2%. This means that the durations in the five cases without reducing batch size are measured to compare the benefit of small batch size. The base completion times without using small batch sizes as shown in Figure 7 are also subject to the rounding error mentioned in the previous section.

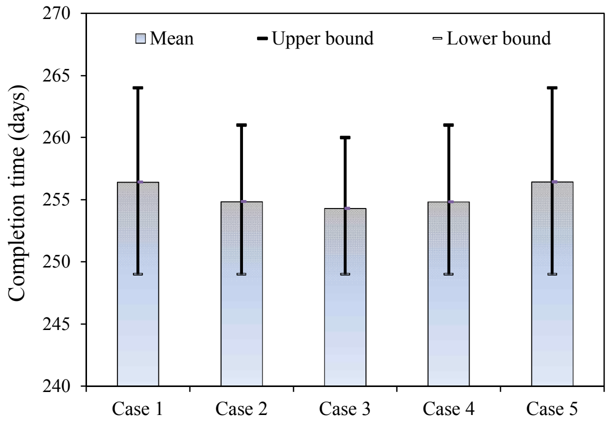


Figure 7. Completion times for batch size of 100% and error rate of 2%

The mean value of completion time for Case 3 is 256.3 days, while for Case 1 and Case 5 it is 258.4 days and 258.5 days, respectively. All of the mean values were determined to be significantly different from each other through a statistical test. Therefore, the impact of small batch size is measured by finding the difference between completion times without using a small batch size and with a small batch size.

The results of the simulation confirm the findings of previous researches: time reduction is achieved by using a small batch size[5,7,14,15] and a larger time reduction is achieved by using a small batch size between well balanced activities[8]. As shown in Figure 8, mean values of completion time for all cases decrease with a small batch size (from 100% to 10%) and the mean values are statistically different from each other.

The impact of balance between productivities on time reduction by small batch size is also confirmed. The amount of time reduction achieved by a reduced batch size is the largest in Case 3, which represents well-balanced productivities between two activities. However, in Case 1 or 5, where productivities are the least balanced, the time reduction achieved is the smallest.

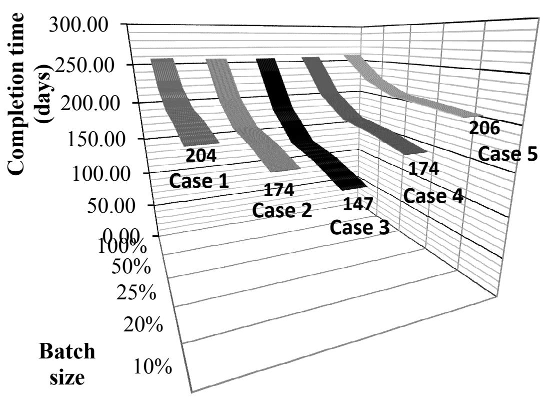


Figure 8. Completion times

5.2 Impact of order of productivities on time reduction due to reduced batch size

Figure 9 shows the amounts of time reduction achieved by using a reduced batch size for the five cases. The amount of time reduction is determined by the difference between completion time (mean value) with a batch size of 100% and completion time with a reduced batch size to minimize the impact of the rounding error. Therefore, the amount of time reduction achieved for a batch size of 100% should be 0.

In Figure 9, it can be interpreted that a pair of construction activities' productivities that are more balanced with each other can take better advantage of using small batch size: this can be seen by comparing the pair of Case 1 and 5, and the pair of Case 2 and 4.

As shown in Figure 9, the amount of the time reduction achieved through a reduced batch size in Case 1 is very similar to that in Case 5. Also, Case 2 and Case 4 are observed to have very similar amounts of time reduction by using a small batch size. It should be noticed that there is a very small amount of difference between the two cases in terms of the amounts of time reduction. However, most amounts of the difference (except the difference in amounts of time reductions between Case 1 and Case 5 under a batch size of 10%) are smaller than 1 day. Considering the rounding errors in the base duration (without using a reduced batch size) as discussed in section 5.1, the differences are not regarded as significant.

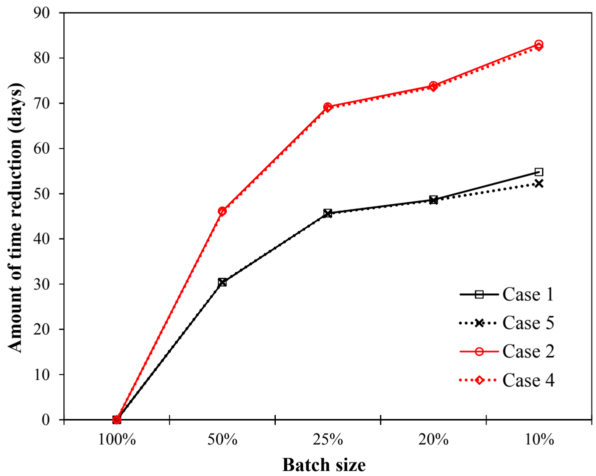


Figure 9. Time reduction due to a reduced batch size

The null hypothesis (H_0) for this study is that order of construction activities' unbalanced productivities affects the amount of time reduction achieved through the use of a small batch size. However, based on the result of the simulation, the null hypothesis should be rejected. Instead, the alternative hypothesis (H_1) is accepted: amount of time reduction achieved through a small batch size is not affected by the order of unbalanced productivities between two activities.

6. Discussion

Using small batch size in a repetitive construction project can reduce overall project duration. However, reducing batch size may require additional cost. Furthermore, Ward and McElwee[14] argue that the adoption of a small batch size by contractors is hindered due to fear of working inefficiently. Also, optimal batch sizes may be different depending on the subcontractor. For example, painting and carpet installation typically use a big batch size, since their productivities are very high[14]. However, batch size of structural framing activity such as the installation of reinforcing rebars or concrete placement in a high-rise apartment building may be smaller than those of painting and carpet installation.

A reduction in project duration can be achieved by using small batch sizes that are balanced. If batch sizes among activities are not balanced, it is recommended to use balanced batch sizes by reducing the batch size of activities with higher productivity[14].

To reduce duration, project managers need to determine which activities' productivities should be changed (reduced) to achieve balanced batch sizes. If there are multiple activities with high productivity (small batch size) and multiple activities with low productivity (big batch size), the project manager's decision becomes more complicated.

The result of this study provides insight to project managers who need to deal with batch size planning/management. It is found that order of activities' productivities which are unbalanced does not affect overall project duration. For this reason, project managers are recommended to reduce batch sizes of activities with a high production rate and to balance batch sizes among multiple activities, irrespective of the sequence of activities.

7. Conclusion

Batch production is common in repetitive construction projects, and reducing batch size is one of the tools to reduce project duration. In addition to size of batch, productivity in each activity is another factor affecting project duration. Balance between productivities can change the amount of time reduction that is achieved by using a small batch size. If productivities are well balanced, it can lead to a shorter duration. However, if productivities are not well balanced, one of the questions regarding balance between productivities is order of productivities: what combination between productivities can take advantage of the benefit of using a small batch size?

This study examined the impact of order of productivities in construction activities on the amount of time reduction that can be achieved by using a small batch size through a computer-based simulation model. Based on the simulation result, the null hypothesis was rejected, and it is concluded that order of construction productivities does not affect the amount of time reduction that can be achieved by using a small batch size.

General contractors whose project is executed by separate specialty contractors (or subcontractors) can plan the overall speed of a project by determining a batch size (or batch sizes). The findings of this study can help general contractors prepare a better plan by understanding the impact of order of productivities on project duration. Although this study is based on a simple computer-based simulation model that includes two construction activities, in future research the area examined should be extended by increasing the number of activities and considering the buffer between activities.

Acknowledgements

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