Quantified Comparison and Analysis of Different Productivity Measurements

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Abstract
Productivity is one of the most important criteria enabling site engineers to evaluate construction performance. A great deal of research has been carried out to investigate an appropriate method of productivity measurement. From these efforts, four different methods have been developed according to the various ways measurements and calculations of productivity are performed: 1) deterministic model-based, 2) simulation model-based, 3) queuing theory-based and 4) actual measurement. However, since there is no reference for productivity measurement based on practical applications, difficulties have arisen in determining which method is appropriate under specific situations. This paper presents a study on the quantified comparisons of results obtained by different methods in order to resolve this limitation. Actual datasets were collected from five construction jobsites where earthmoving was being carried out. Productivity was acquired through four methods. Results showed that the highest value of productivity was yielded by a deterministic model, followed by those obtained by a simulation model. The actual measurement yielded the lowest values of productivity. A queuing theory-based measurement was only available for four datasets due to the limitation of practical application in queue discipline. This study contributes to academia and industry in the field of construction by providing basic characteristics and quantified comparisons of various productivity measurements based on practical applications to actual cases.

Keywords: productivity; earthmoving; deterministic; simulation; queue

1. Introduction
For some time, the construction industry has been regarded as the most conservative industry with high risks compared to other industries. Generally, the success of a construction project depends on well-designed plans and well-planned operations. In order to establish successful plans prior to the actual operations and to provide appropriate resource utilization during actual operations, accurate evaluations of construction performances in progress are required. (Han et al. 2008)

Productivity is considered to be one of the most important criteria allowing construction managers or construction planners to evaluate construction performances (Schaufelberger 1999; Han et al. 2008). There are two research subjects relating to productivity: 1) productivity measurements, and 2) productivity predictions. Productivity measurements function as an indicator of the basic status of the construction operation currently in progress. Productivity predictions are used to estimate the construction performances of a specific future operation.

A considerable amount of research has been conducted to find an appropriate method suitable for productivity measurements that will provide successful results. These efforts have revealed various methods: 1) deterministic model-based measurement, 2) simulation-based measurement, 3) queuing theory-based measurement, and 4) actual measurement (Halpin and Riggs 1992). Many researchers have tried to achieve excellent productivity measurements results based on the various methods described above (Halpin and Riggs 1992; Schaufelberger 1999; Nunnally 2000; Halpin 2006). However, such research is limited to theoretical experiments not based on practical applications.

Construction managers or site engineers have experienced difficulty in selecting the appropriate method for productivity measurements because any references based on a large amount of actual data collected from jobsites were not provided. Accordingly, for ease of application, the productivity of an on-going operation has usually been measured based on the deterministic model. (Han et al. 2006; Han et al. 2008)
As a response to this problem, a new study investigating productivity measurements based on practical cases is required for resolving the limitations of previous research. The study also needs to present a quantified comparison of the results obtained by different productivity measurements so that site engineers are able to identify any basic characteristics and numerical differences between the results by using different types of productivity measurements. Quantified differences calculated by various productivity measurements allow engineers to predict the results obtained by other measurements from the results obtained by measurements actually conducted. This expected outcome is utilized for establishing basic variance ranges of productivity measurements.

2. Literature Reviews of Productivity Measurements

The previous section stated that there have been four different methods introduced so far for productivity measurements. The basic characteristics of each method, as developed in previous studies, are presented in this section.

A deterministic model-based measurement is a common method due to the ease and simplicity of its applications. This method was developed for the simple calculation of the productivity of an earthmoving operation based on the equipment characteristics, equivalent grades, and the haul distance provided by most manufacturers or the historical data collected from jobsites. In addition, this method primarily focuses on the use of time durations that are fixed or constant values, with the assumption that any variability in the task duration is to be ignored (Halpin and Riggs 1992). Halpin and Riggs (1992) presented an example of a simple deterministic model for earthmoving operations, consisting of a scraper for a hauling activity and a pusher dozer for a loading activity, for establishing the deterministic durations for the scraper travel times to and from the fill location. The limitation of this method is that it is seldom able to resolve queuing problems, which occur frequently in many construction situations in spite of simple and easy applications. Productivity measurements obtained by deterministic models mostly utilize references such as R.S Means books and several books containing basic specifications and the estimated productivity of construction equipment (i.e., Caterpillar performance handbook) (Schaufelber 1999; Nunnally 2000).

A simulation-based measurement is the best method for reflecting normal situations where the randomness of cycle time is considered (Halpin 2006). Halpin stated that the influence of random durations on the movement of resources causes various units to become bunched together and consequently there is a rush to arrive at and overload work tasks (Halpin 2006). Simulation models have been extensively developed and broadly used as a management tool within the manufacturing and business industries. The CYCLONE (CYCLic Operation Network) system approach was developed in the early 1970s. This system demonstrated the potential for the modeling and simulation of repetitive construction processes. In 1982, Lluch and Halpin developed a microcomputer version of CYCLONE named MicroCYCLONE. Many improvements to MicroCYCLONE have been developed in the past two decades. In general, construction simulation is conducted in several steps (i.e., site observation, duration and resource data collection, modeling using CYCLONE, running simulation, and sensitivity analysis) (Kannan 1999; Wang and Halpin 2004). While the simulation-based measurement is the most appropriate method to illustrate the actual construction situation prior to the actual operation, the use of this method is very limited due to a lack of knowledge regarding computer programming and modeling (Han and Halpin 2005).

A queuing theory-based measurement is a well-designed method for considering bunching effects that typically occur in a construction operation. This method was originally created and developed for industrial processes. Queuing models are used in a two-link system, which is composed of a processor and calling units. Systems requiring more than two units cannot be used due to the limitation of applications. Generally, calling units (e.g., trucks in earthmoving operations) either move to the processor (e.g., a loader or an excavator in earthmoving operations) directly or wait for processing due to bunching (Halpin and Riggs 1992). This method is limited in the construction field because it can only be used for two types of units. However, it provides quantified bunching effects that cannot be resolved by a determinist model-based measurement.

While an actual measurement is the most accurate method for providing actual productivity, it is regarded as the most difficult method to use since it requires all event times to be recorded and actual productivity to be measured on jobsites. In addition, the accuracy of the measured productivity depends on the skill and experiences of the people who are involved in the task. Accordingly, the reliability of the results obtained by this method is various rather than stable, depending on who is involved and what specific technique is used for measurements. There are several specific techniques that are introduced; 1) stop watch analysis, 2) video taping analysis, 3) time-lapse video taping analysis, and 4) on-board measurement (Han 2005; Han and Halpin 2005; Han et al. 2006; Han et al. 2008).

3. Overviews of Earthmoving Operations

In this study, an earthmoving operation was selected as a targeted construction operation since this operation is expected to present quantified differences in the results obtained by various productivity measurements with a straightforward process due to the simple operation process with a small quantity of construction
Earthmoving is defined as the operation that moves large quantities of earth from one location, generally referred to as the cut or the source, to another location, referred to as the fill or the placement. It is composed of many interacting processes. The major processes are classified as preparation, loading, hauling, dumping and spreading (Hajjar and AbouRizk 1997; Han et al. 2006). Due to the characteristics of earthmoving operations, the planning and performance of conventional earthmoving systems depend on the skills and experience of site managers, equipment operators and surveyors (Schaufelberger 1999; Han et al. 2006).

Commonly, an earthmoving operation requires surveyors to install stakes, which give equipment operators basic visual guidelines, and to reset stakes that have been knocked down during operations. This causes a significant delay because operators must delay work while surveyors recheck the grades and re-install the stakes. Operators also need to verify the resulting surface and calculate the volumes of moved earth and the deviations from the desired design surface in order to provide an interface between the engineering design and the machine operator on-site. The deviation from the desired design surface requires reworking, which is very time-consuming and labor-intensive, and consequently unproductive. It also requires the surveyors and the machine operators to work closely together to produce the final result (Nichols and Day 1999; Han et al. 2006; Han et al. 2008).

4. Data Collection from Jobsites

On construction jobsites, construction managers or site engineers establish a unique fleet management system based on their own strategy and operation. To identify the distinction between results obtained by various productivity measurements, a two-link system needs to be employed on construction jobsites. A total of five construction jobsites were selected where construction raw data was collected for this study. (Han 2005; Han and Halpin 2005; Han et al. 2006; Han et al. 2008)

Table 1. shows the basic descriptions of construction jobsites selected for data collection.

Table 1. Basic Descriptions of Construction Jobsites

| Project | Fleet Organization | Haul Distances (Two ways) |
|---------|--------------------|---------------------------|
| A       | 1 Excavator / 7 Trucks | 4.8 km                   |
| B       | 1 Excavator / 4 Trucks   | 25.4 km                  |
| C       | 1 Excavator / 9 Trucks   | 7.7 km                   |
| D       | 1 Excavator / 2 Trucks   | 1.8 km                   |
| E       | 1 Excavator / 7 Trucks   | 15.1 km                  |

From the projects described in Table 1., data per hour was collected for four or five hours over two or three consecutive days at each jobsite. Thus, 20 separate hourly datasets were collected. Accordingly, each hourly dataset covered a period of multiple cycles. Each dataset represents a significant sample of earthmoving operations in a two-link system due to its project size, different fleet managements, and varied conditions. (Han 2005; Han et al. 2006; Han et al. 2008)

Data was collected through interviews with site personnel and site observations. A stopwatch analysis of pictures was conducted in which all related operations were recorded from the jobsites. This process provided consistent observations for analyzing the event times of each piece of equipment. (Han 2005; Han et al. 2006; Han et al. 2008)

Through these observations and analysis, information that significantly influences the productivity of a system was acquired, such as the travel time, loading time, machine break time and resurveying time. The basic conditions of the jobsite and management, such as haul distance, capacities of excavator buckets and trucks, and the number of pieces of equipment, were also established. (Han 2005; Han et al. 2006; Han et al. 2008)

Table 2. shows a summary of the data collected from the selected job sites.

Table 2. Description of the Collected Data

| Site Observations | Interviews | Field Measurement | Calculation |
|-------------------|------------|-------------------|-------------|
| Stopwatch Analysis with Videotaping | Interviews | Field Measurement | Calculation |
| Machine break time | Bucket capacity | Truck capacity | Soil condition |
| Resurveying time | Number of equipment | Operators' experience | Hauling distance |
| Loading time | Number of loadings | Age of equipment | Productivity |
| Travel time |

Table 3. shows one sample of the collected datasets during one hour.

Productivity measurements using various methods were conducted based on specific types of collected datasets, as shown in Table 3.

5. Productivity Measurements

Through site observations and interviews with site personnel, it was noted that the number of cycles was recorded by either the operators of excavators or the operators of trucks by using a cycle counter on the jobsites; for example, excavator operators clicked one count when the soil was loaded on the tray of each truck. Typically, the foremen collected all the information from these collected cycle numbers and transmitted it to the site managers after completion.
of one working day. Accordingly, this submitted information was the raw data used for yielding daily productivity. (Han 2005)

5.1 Deterministic Model-based Measurement

In order to find the productivity based on the deterministic model, the time durations that were assumed to be deterministic in the model were used as constant values, although the time durations yield various distributions such as beta, normal, or triangular distributions. Calculations of productivity based on a deterministic model are as follows:

- **Excavator cycle time** = 2.19 min. \(\text{cycle}^\text{-1}\)
- **Truck cycle time** = 2.19 min. \(\text{cycle}^\text{-1}\) + 13.60 min. \(\text{cycle}^\text{-1}\) + 1.5 min. \(\text{cycle}^\text{-1}\) + 13.20 min. \(\text{cycle}^\text{-1}\) = 30.49 min. \(\text{cycle}^\text{-1}\)
- **Productivity of excavator** = 60 min/hr / 2.19 min./cycle = 27.39 cycles/hr.
- **Productivity of 9 trucks** = 60 min/hr / 30.49 min. \(\text{cycle}^\text{-1}\) × 9 trucks = 17.71 cycles/hr.

Based on the calculations above, this operation was governed by trucks and measured the productivity of 17.71 cycles/hr. based on a deterministic model.

5.2 Simulation-based Measurement

Due to the complexity of interactions within the construction environment, simulation models can be adopted for analysis of construction operations rather than deterministic models or queuing models. One class of simulation models that has been used to model a chain of queues in which units interact is referred to as the “link-node” model format (Halpin and Riggs 1992). In this study, two types of link–node model formats composed of an excavator and a truck were designed for simulation models. (Han 2005; Han et al. 2006; Han et al. 2008)

One sample of simulation models for project C is shown in Fig.1.

- **Excavator cycle time** = 2.19 min. \(\text{cycle}^\text{-1}\)
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It should be noted that the probability of checking shown at node 3 is assumed to be 0.0001, implying that the checking activity at node 3 seldom occurred during site observations. In the model in Fig.1., the probability of 0.0001 barely influences the result (i.e., the productivity) in 1,000 cycles, which was initially designed as the maximum number of total numbers

Table 3. One Sample of the Collected Datasets in Project C (Unit: minutes)

| Truck No. | Trip No. | Truck Enters Systems | Service Completed Before | Delay Time | Truck Exits System | Service Time | Truck Reenters System | Back Cycle Time |
|-----------|----------|----------------------|--------------------------|------------|-------------------|-------------|-----------------------|-----------------|
| 1         | 1        | 0.00                 | 0.00                     | 0.00       | 2.33              | 2.33        | N/A                   | 24.13           |
| 2         | 1        | 2.33                 | 2.33                     | 4.58       | 2.25              | 2.25        | N/A                   | 25.23           |
| 3         | 1        | 4.58                 | 3.72                     | 6.92       | 2.33              | 2.33        | N/A                   | 34.95           |
| 4         | 1        | 6.92                 | 4.68                     | 10.82      | 3.90              | 3.90        | N/A                   | 35.08           |
| 5         | 1        | 10.82                | (1.38)                   | 15.52      | N/A               | 3.32        | N/A                   | 36.63           |
| 6         | 1        | 15.52                | 3.02                     | 19.10      | 3.58              | 3.58        | N/A                   | 40.23           |
| 7         | 1        | 19.10                | 5.35                     | 21.35      | 2.25              | 2.25        | N/A                   | 41.57           |
| 8         | 1        | 21.35                | 7.43                     | 23.75      | 2.40              | N/A         | 42.23                 | 18.48           |
| 9         | 1        | 23.75                | 8.42                     | 25.63      | 1.88              | N/A         | 49.17                 | 23.53           |
| 1         | 2        | 25.63                | 1.50                     | 28.73      | 3.10              | N/A         | 52.18                 | 23.45           |
| 2         | 2        | 25.23                | 3.50                     | 30.90      | 2.17              | N/A         | 53.20                 | 22.30           |
| 3         | 2        | 30.90                | (4.05)                   | 37.33      | N/A               | 2.38        | N/A                   | 57.45           |
| 4         | 2        | 37.33                | 2.25                     | 39.90      | 2.57              | N/A         | 59.90                 | 20.00           |
| 5         | 2        | 39.90                | 3.27                     | 42.98      | 3.08              | N/A         | 63.95                 | 20.97           |
| 6         | 2        | 42.98                | 2.75                     | 45.85      | 2.87              | N/A         | 66.03                 | 20.18           |
| 7         | 2        | 45.85                | 4.28                     | 49.73      | 3.88              | N/A         | 69.68                 | 19.95           |
| 8         | 2        | 49.73                | 7.50                     | 52.25      | 2.52              | N/A         | 75.33                 | 23.08           |
| 9         | 2        | 52.25                | 3.08                     | 54.93      | 2.68              | N/A         | 79.95                 | 25.02           |
| 1         | 3        | 54.93                | 2.75                     | 56.97      | 2.03              | N/A         | 80.50                 | 23.53           |
of cycles during simulation. This probability was considerably various depending on the numbers of interruptions due to surveyors who were involved in resurveying for the activity of resetting the grade stakes that were knocked out. Interruptions by surveyors for re-staking were not observed in the case shown in Fig.1. However, this interruption typically occurred in other cases. For instance, the probability of resurveying presented at node 3 in Fig.1. would be 0.07 when the interruptions for re-staking are observed 7 times out of 100 cycles for excavating. (Han 2005; Han et al. 2006; Han et al. 2008)

The durations of activity information are summarized in Table 4.

Table 4. Summary of Duration Information for One of the Collected Datasets in Project C

| Node | Activity | Distributions (Durations: minutes) |
|------|----------|-----------------------------------|
| 2    | An excavator prepares for earth loading | Deterministic (0.5) |
| 3    | Check for grade stakes knocked out | Deterministic (0.1) |
| 6    | A surveyor checks | Deterministic (0.78) |
| 8    | Stockpile | Deterministic (0.4) |
| 31   | An excavator returns | Deterministic (0.3) |
| 53   | An excavator loads the earth on trucks' bed | Beta (0.57 3.48 0.66 1.38) |
| 55   | A truck travels to dumping area | Beta (9.17 14.30 0.57 1.36) |
| 56   | A truck dumps | Deterministic (1.5) |
| 58   | A truck returns for loading the earth | Beta (7.91 12.34 1.25 1.13) |

The duration information recognized by the input module of the model in Table 4. were deterministic and beta distributions. Deterministic durations were used for activities where small variations are observed, while a beta distribution was used for activities where large variations are observed. According to AbouRizk and Halpin (1992), a beta distribution is recommended for use in modeling random input processes of construction durations for simulation studies because beta distribution can reflect a flexible distribution (AbouRizk and Halpin 1992; Han 2005; Han et al. 2008).

Table 5. shows basic information of the quantity of initial resources used in the simulation model in Fig.1.

Table 5. Summary of Initial Resources for One of the Collected Datasets in Project C

| Node | Resource         | Quantity |
|------|------------------|----------|
| 1    | Ground initial resource | 1        |
| 7    | A surveyor       | 1        |
| 33   | An excavator     | 1        |
| 59   | Trucks           | 9        |

The results of conducting a simulation model associated with all information described in this section are 17.48 cycles / hour.

5.3 Queuing Theory-based Measurement

As noted previously, there is a limitation with productivity measurement based on a deterministic model, due to the difficulty in reflecting various durations that commonly occur in an actual construction operation. As an alternative, a queuing theory is introduced as a tool capable of overcoming this limitation. Consequently, the application of the queuing theory to data collected by field observations provided more reliable and practical results than that of a deterministic model.

Halpin and Riggs (1992) described the queuing model as follows:

"Many situations in which units are repetitively processed can be viewed as queuing or waiting-line problems. Queuing models can be used to model systems in which two units, designated processor and calling unit, interact with one another. Commonly, units that are processed move directly to the processor or are delayed because the processing unit is busy with another unit."

According to the text by Halpin and Riggs (1992), the productivity based on a queuing theory is calculated as follows.

\[
\text{Productivity} = (\text{PI}) \times L \times C \times \mu \quad \text{Equation (1)}
\]

where,
\[
\text{PI} = \text{Productivity Index (i.e., percent of the time that the system contains units that are loading).}
\]
\[
L = \text{Period of time considered}
\]
\[
C = \text{Capacity of the unit loaded}
\]
\[
\lambda = 1 / \text{the average time a unit stays outside the system}
\]
\[
\mu = \text{Processor rate} = 1 / \text{the average service time}
\]

The PI value described above is achieved from Queuing nomographs shown in the text by Halpin and Riggs (1992) using the utilization factor (\(\lambda/\mu\)).

The equation for calculating productivity based on a queue theory requires an initial search for values of \(\lambda\) and \(\mu\). It should be noted that \(\lambda\) is calculated in arrivals per hour and \(\mu\) is calculated in loads per hour. The mean service time in minutes for \(\mu\), denoted as \(T_s\), is calculated from the summation of service times divided by the total number of trips per hour. The mean arrival time in minutes for \(\lambda\), denoted as \(T_a\), is calculated from the summation of back cycle times divided by the total number of trips per hour. (Han 2005)

Accordingly, values of \(\lambda\) and \(\mu\) for datasets presented in Table 3. were found in Table 6.

Based on the calculation of \(\lambda\) and \(\mu\) in Table 6., the hourly productivity based on a queue theory of one sample dataset in project C was calculated by Equation...
It is difficult to apply the field application of the queuing theory to cases that break from queue discipline, where all activities interacting in a queuing system are continuously operated without any breakdown (Halpin and Riggs 1992). Many unexpected factors can break repeated interactions of construction activities. For instance, interruptions by surveyors for re-staking and resurveying, or a breakdown of equipment, can be factors that break queue discipline. Thus, field applications based on a queuing theory can only be applied to a limited number of special cases that have no interruptions for re-staking and surveying or equipment breakdown. In this study a queuing theory was applied to four datasets out of a total of 20.

### 5.4 Actual Measurement

In common earthmoving operations, operators of trucks clicked once when they had finished the dumping operation. This implies that the daily productivity is calculated by the recorded numbers of dumping during one working day, noted as cycles/day. There are two techniques used to measure hourly productivity. The first technique is to measure the number of cycle times by operations during one hour. The second technique is derived by dividing the daily productivity by the total working hours per day, noted as cycles/hours. (Han 2005; Han et al. 2006; Han et al. 2008)

Generally, a site manager collected the number of cycles from all truck operators and added them together to obtain the daily productivity. The productivity data obtained by actual measurement was collected using two resources: 1) the daily report record of the site manager, or 2) calculations derived from dividing the recorded number of dumping by the total durations. (Han 2005; Han et al. 2006; Han et al. 2008)

An actual measurement of productivity, as one of the methods of productivity measurements discussed in this study, is conducted as for the method previously described. The productivity based on actual measurements observed on jobsites was 16.42 cycles/hr.

### 6. Comparisons of Results from Various Productivity Measurements

Identical procedures and assumptions as those previously presented were applied to all productivity measurements. Table 7. shows the productivity comparison for all of the datasets collected from the jobsites visited. The comparison rates shown in Table 7. are the ratios of the productivity obtained by each method to that of the actual measurements. As shown in Table 7., only four datasets were used to present the results obtained by a queue theory-based measurement because there were no interruptions in the processing.

From Table 7. it can be seen that the queuing theory-based measurement was applicable only to the third, first and fourth dataset, and the first dataset of project A, C, C, and E, respectively, due to the limitation in the application as described previously. Accordingly, these four datasets out of a total of 20 were utilized to compare the results obtained from four different productivity measurements.

Table 8. shows the quantified comparison of results obtained from four different productivity measurements.

According to Tables 7. and 8., it can be seen that, among other methods, the deterministic model-based measurement yielded the highest values of productivity. The results of the simulation model-based measurement followed those of the deterministic model-based measurement, while those of the actual measurement yielded the lowest values of productivity. Evidence for this result is provided by the graph in Fig.2., which illustrates the quantified differences of the four different productivity measurements.

From the values of averages and standard deviations for comparison rates referred to in Table 7., the average values of comparison rates, which are

| Truck No. | Trip No. | $T_a$ | $\lambda$ | Load | $T_s$ | $\mu$ |
|-----------|---------|-------|----------|------|-------|-------|
| 1         | 3       | 22.93 | 2.62     | 3    | 2.49  | 24.11 |
| 2         | 2       | 21.48 | 2.79     | 2    | 2.21  | 27.17 |
| 3         | 2       | 24.08 | 2.49     | 2    | 2.36  | 25.44 |
| 4         | 2       | 22.13 | 2.71     | 2    | 3.23  | 18.56 |
| 5         | 2       | 21.04 | 2.85     | 2    | 3.20  | 18.75 |
| 6         | 2       | 20.66 | 2.90     | 2    | 3.23  | 18.60 |
| 7         | 2       | 20.08 | 2.99     | 2    | 3.07  | 19.57 |
| 8         | 2       | 20.78 | 2.89     | 2    | 2.46  | 24.41 |
| 9         | 2       | 24.28 | 2.47     | 2    | 2.28  | 26.28 |

$\sum = 19$ Avg. ($T_a$) = 21.94 Avg. ($\lambda$) = 2.73 $\sum = 19$ Avg. ($T_s$) = 2.72 Avg. ($\mu$) = 22.02

(1) as follows:

$$\text{Productivity} = (P_l) \times L \times C \times \mu$$

$$= 0.79 \times 1 \times 1 \times 22.02$$

$$= 17.40 \text{ cycles/hr.}$$
Table 7. Quantified Comparison of Various Productivity Measurements

| Project | Dataset | Actual Measurement Productivity | Productivity Measurements (Unit: cycles/hr.) | Productivity Rates(%) | Deterministic Model Productivity Rates(%) |
|---------|---------|---------------------------------|---------------------------------------------|-----------------------|------------------------------------------|
| A       | 1       | 18.53                           | N/A                                         | N/A                   | 19.10                                    |
|         | 2       | 13.29                           | N/A                                         | N/A                   | 14.22                                    |
|         | 3       | 24.51                           | 24.55                                       | 100.16                | 26.00                                    |
|         | 4       | 15.97                           | N/A                                         | N/A                   | 16.13                                    |
|         | 5       | 19.37                           | N/A                                         | N/A                   | 19.82                                    |
|         | 1       | 4.05                            | N/A                                         | N/A                   | 4.17                                     |
|         | 2       | 3.50                            | N/A                                         | N/A                   | 3.74                                     |
| B       | 1       | 16.42                           | 17.40                                       | 105.97                | 17.48                                    |
|         | 2       | 8.09                            | N/A                                         | N/A                   | 8.38                                     |
|         | 3       | 15.19                           | N/A                                         | N/A                   | 15.52                                    |
|         | 4       | 18.14                           | 18.19                                       | 100.28                | 18.56                                    |
| C       | 5       | 16.04                           | N/A                                         | N/A                   | 16.12                                    |
|         | 1       | 4.39                            | N/A                                         | N/A                   | 4.57                                     |
|         | 2       | 3.26                            | N/A                                         | N/A                   | 3.37                                     |
|         | 3       | 3.87                            | N/A                                         | N/A                   | 3.88                                     |
| D       | 1       | 15.46                           | 15.53                                       | 100.45                | 16.14                                    |
|         | 2       | 15.60                           | N/A                                         | N/A                   | 15.94                                    |
|         | 3       | 14.31                           | N/A                                         | N/A                   | 16.90                                    |
|         | 4       | 12.20                           | N/A                                         | N/A                   | 12.72                                    |
|         | 5       | 14.75                           | N/A                                         | N/A                   | 15.70                                    |
| E       | 1       | 15.46                           | 15.53                                       | 100.45                | 16.14                                    |
|         | 2       | 15.60                           | N/A                                         | N/A                   | 15.94                                    |
|         | 3       | 14.31                           | N/A                                         | N/A                   | 16.90                                    |
|         | 4       | 12.20                           | N/A                                         | N/A                   | 12.72                                    |
|         | 5       | 14.75                           | N/A                                         | N/A                   | 15.70                                    |
| Avg.    |        |                                 |                                             | 101.71                | 104.37                                   |
| Std.    |        |                                 |                                             | 2.84                  | 3.84                                     |

Note: A, Actual Measurement  B, Queuing Theory  C, Simulation Model  D, Deterministic Model

Table 8. Quantified Comparison of Results by Four Different Productivity Measurements

| PJ | Datasets | Productivity Measurement (Unit: cycles/hr.) |
|----|----------|---------------------------------------------|
| A  | 3        | 24.51                                       |
|    | B        | 24.55                                       |
|    | C        | 26.00                                       |
|    | D        | 26.37                                       |
| C  | 1        | 16.42                                       |
|    | B        | 17.40                                       |
|    | C        | 17.48                                       |
|    | D        | 17.71                                       |
| C  | 4        | 18.14                                       |
|    | B        | 18.19                                       |
|    | C        | 18.56                                       |
|    | D        | 18.78                                       |
| E  | 1        | 15.46                                       |
|    | B        | 15.53                                       |
|    | C        | 16.14                                       |
|    | D        | 16.38                                       |

Note: A, Actual Measurement  B, Queuing Theory  C, Simulation Model  D, Deterministic Model

The results obtained from the four productivity measurements that were conducted based on practical application indicated that the highest value of productivity was yielded by the deterministic model-based measurement, followed by the values of productivity obtained from the simulation model-based measurement. However, there was a limitation in the application of the queuing theory. A difficulty arises in the practical application of the queuing theory when it is applied to cases that have unexpected interruptions in a queuing system. The practical application of this method is limited because many unexpected factors interrupt the repetitive operations of common construction activities.

It was found that the differences between the results obtained by the four different methods were within an 11.33% range, which was based on the average values of comparison rates between the deterministic model-based measurement and the actual measurement. The remainder of the results obtained by both the simulation model-based and the queuing theory-based measurements attained positions between 0% and 11.33%, a maximum average difference.

Based on the analysis of quantified comparisons, it can be concluded that the deterministic model-based measurement provides optimistic results, since no consideration needs to be made for waiting or delays caused by unexpected factors that commonly exist on construction sites. The simulation model-based measurement presents superior results over the actual measurement and less favorable results than the deterministic model with reflecting bunching effects.

The results obtained from the four productivity measurements that were conducted based on practical application indicated that the highest value of productivity was yielded by the deterministic model-based measurement, followed by the values of productivity obtained from the simulation model-based measurement. However, there was a limitation in the application of the queuing theory. A difficulty arises in the practical application of the queuing theory when it is applied to cases that have unexpected interruptions in a queuing system. The practical application of this method is limited because many unexpected factors interrupt the repetitive operations of common construction activities.

7. Conclusions

This paper presented a study on the quantified comparison of results obtained by using four different productivity measurements: 1) deterministic model-based measurement, 2) simulation-based measurement, 3) queuing theory-based measurement, and 4) actual measurement.

These methods have been commonly utilized in both academia and industry in the field of construction. However, construction managers or site engineers barely manage to select the appropriate method for productivity since there is no reference available that is capable of providing actual comparisons based on the collected data. A total of 20 actual hourly datasets were collected from five construction jobsites in order to present the quantified differences between them.
This study can provide contributions to academia by suggesting a methodology for pursuing numerical comparisons. In addition, the quantified differences of the measured productivity between the actual measurement and the alternative measurements (i.e., the simulation model and the deterministic model) could assist construction managers or site engineers to estimate productivity by using methods other than actual measurements.

However, this study reveals a limitation in the research, whereby all findings were based on earthmoving operations that were specifically two or three-link systems. In order to establish a more reliable application, various datasets with a large amount of raw data in a range of construction operations need to be collected and processed. Moreover, the comparison results presented in this study are restricted to only the proposed operations under limited situations. If these measurements are applied to other operations, the comparison results may be different. Accordingly, further studies for development and application to various construction operations are required.

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