Implementation of Construction Performance Database Prototype for Curtain Wall Operation in High-Rise Building Construction

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Abstract

Project process planning is implemented based mainly on the experience of engineers, which can lead to critical cost overruns and delays. This suggests a need for precise planning based on reliable data to prevent serious problems in project management. Accurately predicting productivity is one of the most important issues in process planning. In this regard, simulation methodology is considered to be an effective tool for predicting productivity. However, it is limited in terms of applications to actual sites due to modeling and coding difficulties. Although many researchers have developed various methodologies for addressing such difficulties, no study has focused on developing an optimized model for site personnel. We analyze unit cost and productivity by using a simulation technique. In addition, we standardize data by using statistical methods, and develop a database prototype. In this way, we highlight appropriate analytic and predictable methods for the construction field. In addition, the proposed statistical analysis provides objective insights into experimental construction data.

1. Introduction

1.1 Aim and Objectives

Recent years have witnessed an increasing number of high-rise construction projects, and construction processes have become increasingly complicated (Kim and Kim 2010). Curtain wall systems have been widely employed in the construction of high-rise buildings because they are light in weight, and units of them can be produced in a factory. The curtain wall installation process requires precise planning. However, in most construction projects, this planning implementation is based mainly on the experience of site personnel. Appropriate process planning requires the continuous analysis and prediction of construction performance (Lim 2009). Simulation has been recognized as an appropriate methodology for analyzing and predicting construction performance, but is limited in terms of applications to actual sites because of modeling and coding difficulties (Shin *et al*. 2012). An emerging methodology based on excellent outcomes by simulation application resulting in reliable performance prediction is highly demanded Many researchers have indicated that database structures would be one of the best solutions to resolve this limitation since a database is capable of providing users with feasible information that was analyzed by specific tools. In this regard, the objective of this study is to develop a prototype database by using simulation to overcome such limitations, and to suggest a more reliable decision-making tool for site personnel. To achieve this objective, we considered several issues: 1) the specific formats of construction simulation implementation, 2) a detailed procedure for finding statistic locations of the selected values, 3) the frameworks of the database structure and a prototype of a screen shot presenting specific categories of output information, and 4) a feasible case showing all procedures and outputs.

1.2 Methodology and Scope

This study was conducted using the following procedures. The curtain wall operation was targeted as the subject of our methodology application, as described in Section 1.1. Then,

1) We performed a literature review of the curtain wall system and fundamental methodologies, such as simulation techniques and various methods for construction productivity predictions.

2) Site visits and observations of activities of curtain wall operations were conducted at three relevant sites.

3) Data collection was achieved through interviews with site engineers, and measurements of cycle times

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and hourly productivity were made.

4) Simulation modeling was performed based on the collected information of the detailed working processes, and on the cycle times for each activity.

5) An analysis of construction performance was performed in terms of unit cost (US Dollars/cycle) and productivity (cycles/hour) through simulation.

6) Data were sorted and stored with information on the number of resources, the values of productivity and costs, and the total times in the database.

7) Data standardization was performed using Z conversion based on statistical methods, with the assumption of a normal distribution for the acquired information in the database.

8) The developed database prototype suggested results (the productivity) of simulation implementation depending on selected scenarios.

2. Literature Review
2.1 High-rise Curtain-wall Operation

Curtain wall systems have been widely used in high-rise construction because of their numerous advantages. For example, curtain wall units are light, and most are manufactured in factories—not at the construction site—thereby reducing the space needed for unit stocking and thus the construction time. We analyzed the procedure for installing a curtain wall system by dividing it into several processes. Table 1. shows these processes, and Fig.1. shows the installation procedure (Kim 2012; Lee *et al*. 2011).
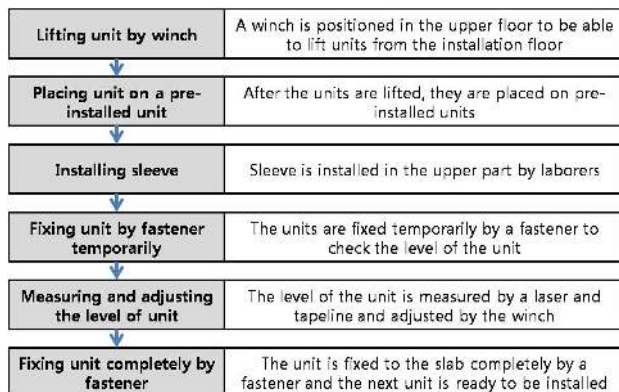
Lifting unit by winch	A winch is positioned in the upper floor to be able to lift units from the installation floor
Placing unit on a pre-installed unit	After the units are lifted, they are placed on pre-installed units
Installing sleeve	Sleeve is installed in the upper part by laborers
Fixing unit by fastener temporarily	The units are fixed temporarily by a fastener to check the level of the unit
Measuring and adjusting the level of unit	The level of the unit is measured by a laser and tapeline and adjusted by the winch
Fixing unit completely by fastener	The unit is fixed to the slab completely by a fastener and the next unit is ready to be installed

Fig.1. Curtain Wall Unit System Installation Process

2.2 Construction Simulation

Simulation involves modeling processes or experiments with actual systems to improve or analyze a given system. Our method of construction simulation consists of collecting data, modeling using CYCLONE (cyclic operation network) software, and conducting and analyzing simulation models (Halpin and Riggs 1992). Various simulation methods have been used for analyzing the productivity of construction operations and predicting construction performance (Kannan 1999; Wang and Halpin 2004; Han *et al*. 2006; Han and Lee 2008).

Table 1. Curtain Wall Unit System Operation Procedure

Truck arrival	Forklift ready	Unit unloading
Unit moved	Unit placed in lifting area	Lift preparation
Crane connection	Unit being lifted	Unit placed in installation area
Installation preparation	Fastener installation	Winch lowering
Preparation	Unit lifting	Unit fitting
Fastener installation (temporary)	Level measurement and modification	Fastener fixing
Sleeve placement	Winch removal	

CYCLONE, developed by Halpin and Woodhead (1976), is a typical construction simulation tool for repeated processes. A model can be easily developed by considering resources, time, and logistical relationships between tasks (Halpin and Woodhead 1976). In addition, CYCLONE has been used for data generation wherein the raw data are insufficient to function as input data for other prediction methods such as linear regression and artificial neural networks (Han and Halpin 2005; Han *et al*. 2008; Lee *et al*. 2011). However, previous studies have highlighted the limitations of CYCLONE in terms of practical applications because of its implementation difficulties.

2.3 Productivity Assessment and Prediction

Construction productivity is considered to be a fundamental factor in determining if the targeted operations are well achieved. Many studies have

suggested various methods for productivity assessments (Adeli 2001; Han and Lee 2008; Han 2010). Also, many studies have been performed to examine productivity using simulation techniques, statistic tools, and artificial neural networks (Adeli 2001; Graham and Smith 2004; Lowe *et al.* 2006; Ali *et al.* 2007; Han *et al.* 2008; Han 2010). Several studies have considered models for overcoming the problem of data shortages for decision-making tool applications. Multiple regression analysis has been widely used for performance predictions in construction. Artificial neural networks alone, or combined with fuzzy approaches, have been used for productivity prediction (Carpenter *et al.* 1991; Adeli 2001; Lu *et al.* 2006). Several studies have extended the scope further by considering data generation in order to acquire more feasible results (Han *et al.* 2008). All of these efforts indicate the limitation of practical applications in that users hardly utilize these models with no professional knowledge of various tools such as statistics, artificial intelligence and so on. Accordingly, the system of a database where the results via these kinds of tools are systemically controlled can provide users with an efficient way to select feasible performance data prior to actual operations.

3. Data Collection and Analysis
3.1 Site Description
Our data were collected from three construction sites employing curtain wall systems. Tables 2.-4. describe these sites.
3.2 Simulation Modeling and Productivity Analysis
Construction productivity was analyzed using the simulation models shown in Figs.2.-4. Fig.2. shows a simulation model of the unloading process, to which this model was applied (Lee *et al.* 2011). The results indicate that preparation and truck standby times have the greatest impact on productivity, which implies that reducing the truck standby time can improve productivity. We conducted a simulation study by considering various combinations of construction equipment. Table 5. shows the productivity analyzed using the simulation model. In this study, the unloading process was simulated with one to five trucks and forklifts.

Sites A and B use hoists to lift curtain wall units, and Site C uses a crane. Therefore, two simulation models were developed and used as shown in Figs.3. and 4. The model shown in Fig.3. was applied to Sites A and B. The model shown in Fig.4. was applied to Site C. The moving time is the amount of time required for workers to move a unit to the lift area. The results indicate that the moving time has the greatest impact on productivity, thereby implying a need for allocating an appropriate space for stocking units as close as possible to the lift area. The lifting time varies according to the floor. The lifting process was simulated by using one to two hoists and cranes with

one to two groups of four workers. Table 6. shows the productivity analyzed using the simulation model.

Table 2. Site A Description

Site image	
Name	Bucheon joongdong apartment complex
Location	Kyengki-do Bucheon wonmi-gu joongdong 1116-12
Purpose	572 households, sales facilities, sports facilities, culture and assembly facilities
Structure	Reinforced Concrete
Size	Basement 7 floors, 66 floors (maximum height 238.95 m)

Table 3. Site B Description

Site image	
Name	Songdo centrod (central)? complex
Location	Incheon yeonsu-gu songdo-dong 30-3,4
Purpose	Offices
Structure	Reinforced Concrete and Steel Reinforced Concrete
Size	34 floors

Table 4. Site C Description

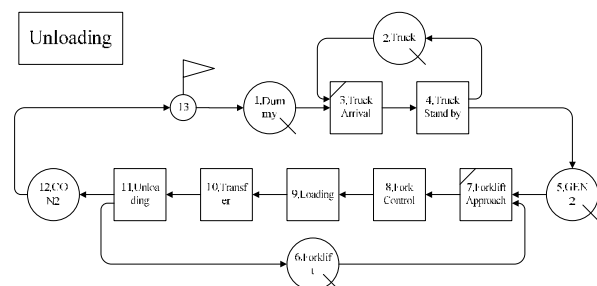|	
Site image	
Name	Songdo C8-2BL complex
Location	Incheon Yeonsu-gu songdo-dong 29-13
Purpose	Offices, sales facilities
Structure	Reinforced Concrete and Steel Reinforced Concrete
Size	Basement 4 floors, 35 floors (maximum height 155 m)

Fig.2. Unit Unloading Process Simulation Model

Table 5. Unloading Process Productivity Analysis

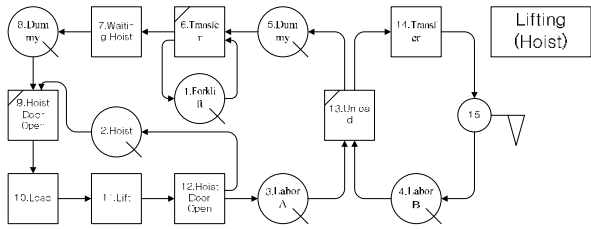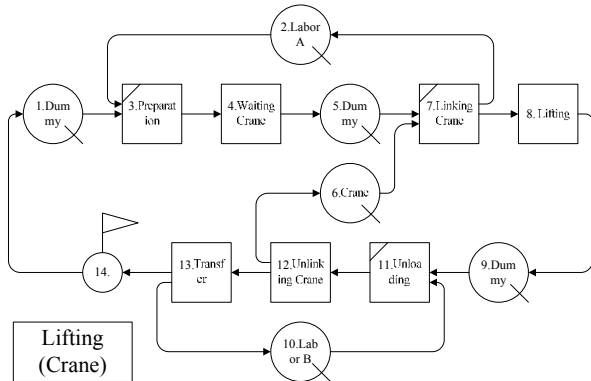| Site	Truck	Forklift	Productivity [cycles/hour]
A	1	1	10.39
B	1	1	5.14
C	1	1	5.03
A	2	2	15.91
B	2	2	6.56
C	2	2	6.66

Fig.3. Lifting Process Simulation Model (Hoist)

Fig.4. Lifting Process Simulation Model (Crane)

Table 6. Lifting Process Productivity Analysis

Site	Forklift	Hoist/Crane	Crew 1	Crew 2	Productivity [cycles/hour]
A	1	1	1	1	4.09
B	1	1	1	1	5.01
C	1	1	1	1	3.68
A	2	2	2	2	9.01
B	2	2	2	2	10.54
C	2	2	2	2	7.50

Fig.5. shows our simulation model of the installation process. The results of the simulation indicate that preparation and fastener-fixing times have the greatest impact on productivity. The installation process depends mainly on the communication between up and down parts. A unit is prepared for its installation in the down part, while the fastener is being fixed and the level is measured in the up part. Table 7. shows the productivity analyzed using the simulation model. The unit installation process was simulated using one to five winches, and two groups of one to five workers. The overall data collected reflect 58 cycles: 10 cycles of the unloading process, 15 cycles of the lifting process, and 33 cycles of the installation process. Simulation models based on real process data were developed, and

the productivity of each process was analyzed. Various combinations of equipment were simulated. The total number of datasets obtained from simulation is 75 for the unloading process, 192 for the lifting process, and 375 for the installation process.
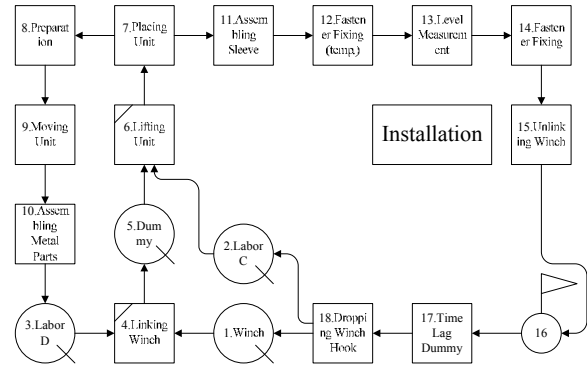

Fig.5. Installation Process Simulation Model

Table 7. Installation Process Productivity Analysis

Site	Winch	Up	Down	Productivity [cycles/hour]
A	1	1	1	4.18
B	1	1	1	3.66
C	1	1	1	4.66
A	2	2	2	8.66
B	2	2	2	8.02
C	2	2	2	9.55

3.3 Unit Cost Analysis

The unit cost was analyzed using Eq. (1), which is based on productivity data obtained through simulation. The cost of labor and equipment used in this study was obtained through interviews with site personnel, and from the Cost Estimation Standards in Korea.

$$Unit\ Cost = \frac{L.C + E.C}{P} + M.C \qquad (1)$$

where,
L.C. = Labor cost [US dollars/hour]
E.C. = Equipment cost [US dollars /hour]
P = Productivity [cycles/hour]
M.C. = Material cost [US dollars /hour]

The unloading, lifting, and installation processes were analyzed separately, and the cost of the curtain wall unit was applied only to the installation process

Table 8. Unloading Process Unit Cost Analysis

Site	Truck	Forklift	Unit cost [USD/cycle]
A	1	1	2.63
B	1	1	5.31
C	1	1	5.42
A	2	2	3.43
B	2	2	8.32
C	2	2	8.19

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Table 9. Lifting Process Unit Cost Analysis

Site	Forklift	Hoist/Crane	Down	Up	Unit cost [USD/cycle]
A	1	1	1	1	14.89
B	1	1	1	1	12.16
C	1	1	1	1	16.53
A	2	2	2	2	13.52
B	2	2	2	2	11.56
C	2	2	2	2	16.24

Table 10. Installation Process Unit Cost Analysis

Site	Winch	Up	Down	Unit cost [USD/cycle]
A	1	1	1	1,378.09
B	1	1	1	1,380.15
C	1	1	1	1,376.62
A	2	2	2	1,377.59
B	2	2	2	1,378.72
C	2	2	2	1,376.29

to prevent cost overlaps. The results for the unit costs are shown in Tables 8.-10.. The numbers of workers and equipment units shown in the figures are consistent with the results of the productivity analysis.

3.4 Data Standardization

The normal distribution, which is one of the most important distributions in statistics, has numerous mathematical properties, and the results of repeated experiments demonstrate a normal distribution (Ko 1998). In construction, the strength of reinforced bars follows a normal distribution. Equation (2) shows the probability density function of the normal distribution:

$$f(x:\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad (2)$$

where,
μ = Mean
σ = Standard deviation
$\sigma > 0$ and $-\infty < \mu < \infty$

A distribution with a mean of μ and a variance of σ^2 is referred to as a normal distribution, and is expressed as X-N(μ, σ^2). Here, f(x: μ ,σ) is a normal distribution only if the area under the function is 1. In particular, transforming the distribution into Z produces $\mu=0$ and $\sigma=1$, which is referred to as the standard normal distribution (Kim and Yoon 2004; Ko 1998). In this study, data on construction performance were standardized using Eq. (3) to allow for a comparison between the unit cost and productivity. In addition, this standardization produced information on ranges of specific data in the distribution. Tables 11.-16. show the standardized data, and Fig.6. provides a sample range for the distribution.

$$Z = \frac{x-\mu}{\sigma} \qquad (3)$$

Table 11. Standardization of Unloading Process Productivity

Site	Truck	Forklift	Z	Range (%)
A	1	1	0.2754	60~65
B	1	1	-0.9434	15~20
C	1	1	-0.9685	15~20
A	2	2	1.5568	90~95
B	2	2	-0.6133	25~30
C	2	2	-0.5896	25~30

Table 12. Standardization of Lifting Process Productivity

Site	Forklift	Hoist/Crane	Down	Up	Z	Range (%)
A	1	1	1	1	-1.4631	5~10
B	1	1	1	1	-1.2516	10~15
C	1	1	1	1	-1.0130	15~20
A	2	2	2	2	-0.3293	35~40
B	2	2	2	2	0.0234	50~55
C	2	2	2	2	1.2605	85~90

Table 13. Standardization of Installation Process Productivity

Site	Winch	Up	Down	Z	Range (%)
A	1	1	1	-1.0075	15~20
B	1	1	1	-1.1220	10~15
C	1	1	1	-0.9036	15~20
A	2	2	2	-0.9641	15~20
B	2	2	2	-1.0154	15~20
C	2	2	2	-0.8786	15~20

Table 14. Standardization of Unloading Process Unit Cost

Site	Truck	Forklift	Z	Range (%)
A	1	1	-1.2900	5~10
B	1	1	-0.8300	20~25
C	1	1	-0.8104	20~25
A	2	2	-1.1523	10~15
B	2	2	-0.3146	35~40
C	2	2	-0.3364	35~40

Table 15. Standardization of Lifting Process Unit Cost

Site	Forklift	Hoist/Crane	Down	Up	Z	Range (%)
A	1	1	1	1	0.1954	55~60
B	1	1	1	1	-0.2828	35~40
C	1	1	1	1	-1.0819	10~15
A	2	2	2	2	-0.0444	45~50
B	2	2	2	2	-0.3884	30~35
C	2	2	2	2	-1.1202	10~15

Table 16. Standardization of Installation Process Unit Cost

Site	Winch	Up	Down	Z	Range (%)
A	1	1	1	-0.8995	15~20
B	1	1	1	-0.7140	20~25
C	1	1	1	-1.0320	15~20
A	2	2	2	0.0968	50~55
B	2	2	2	0.2265	55~60
C	2	2	2	-0.0910	45~50

4. Database Prototype Development

Unit costs and productivity were analyzed for the three construction sites. The unit cost, labor, equipment, and productivity are linked together as one dataset collected from each site. Fig.7. shows the
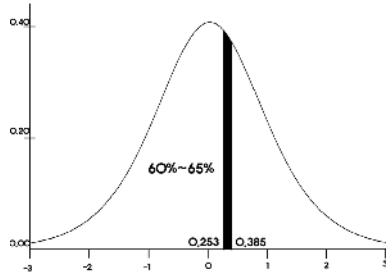
Fig.6. Rank Example

proposed database prototype, which was developed as follows (Lee *et al.* 2012):

1) We focused on curtain wall systems, but this approach is expected to be applicable to other systems. Therefore, in further studies, this option can be changed to the targeted operation which users are interested in.

2) The operation chosen in option 1 is divided into the main processes. In the case of curtain wall systems, option 2 is divided into the unloading, lifting, and installation processes.

3) Option 3 allows the user to choose the number of datasets to be shown in the database. For example, if the user selects 30, the database will show only the 30 datasets.

4) Construction data vary even for the same site and operation. Therefore, in option 4, the user can choose the order of datasets based on the lowest unit cost, the minimum use of resources, and the highest productivity. The use of option 4 enables the user to obtain information on current conditions of the site.

5) Option 5 shows the site name.

6) Option 6 shows the resources.

7) Option 7 shows the productivity expected by using the resources chosen in option 6.

8) Option 8 shows the cycle time expected by using the resources chosen in option 6.

9) Option 9 shows the unit cost expected by using the resources chosen in option 6.

10) Option 10 shows the Z score for the unit cost and productivity.

11) Option 11 shows the distribution of data.

11-1) Option 11-1 shows the overall distribution of productivity.

11-2) Option 11-2 shows the overall distribution of unit cost.

11-3) Option 11-3 shows ranges of productivity for selected data.

11-4) Option 11-4 shows ranges of the unit cost for selected data.

5. Feasible Case

We considered a feasible case with unit cost and productivity predictions based on the proposed methodology. The following assumptions were made:

Unloading process:
1) Four trucks are used.
2) Three forklifts are used.

Lifting process:
1) A hoist is used to lift curtain wall units.
2) Two hoists are used.
3) Three workers are responsible for lifting curtain wall units.
4) Two workers are responsible for receiving curtain wall units on the installation floor.

Installation process:
1) Two winches are used.
2) Two workers are responsible for the up part.
3) Two workers are responsible for the down part.

Table 17. shows data on the unit cost and productivity that can be obtained by the user. Table 18. shows the ideal data (i.e., data for the highest productivity and the lowest unit cost) that can be obtained by the user. In addition, the database prototype shows the overall distribution and ranges of the data. The user can consider site-specific situations and make appropriate decisions based on reliable data. Fig.8. shows the ranges of the unit costs and productivity of the installation process shown in Table 18. The left side of Fig.8. shows the productivity, and the right side shows the unit cost. The user can see that
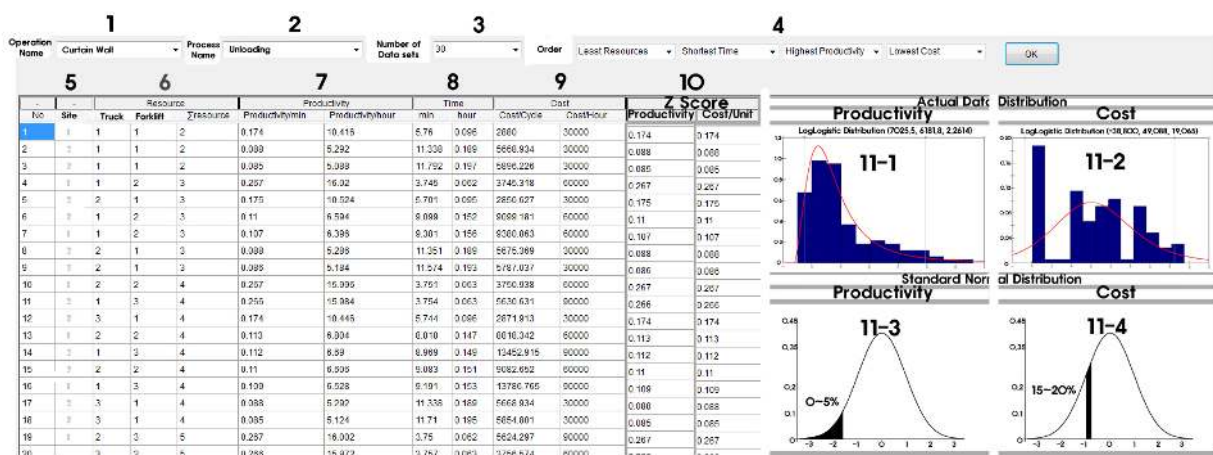

Fig.7. Database Description

the ideal range is 55% to 60% for productivity and 10% to 15% for unit cost. For example, in this case, if the construction site is experiencing a delay, then the user can determine that the low range is 10% to 15% and increase it to enhance construction productivity.

Table 17. Productivity and Unit Cost Prediction Example

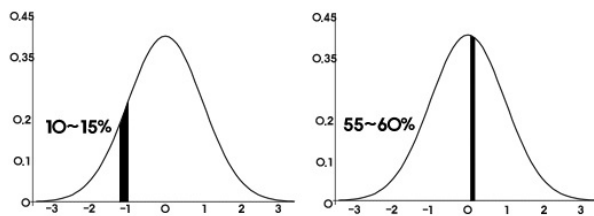| Process	Equipment	No.	Productivity [cycles/hour]	Unit cost [USD/cycle]
Unloading	Truck	4	16.13	5.07
	Forklift	3	6.71	12.19
			6.37	12.84
Lifting	Hoist	2	12.55	11.05
	Down	3	14.87	9.33
	Up	2		
Installation	Winch	2	8.66	1,377.59
	Up	2	8.02	1,378.72
	Down	2	9.55	1,376.29

Fig.8. Rank of Productivity and Unit Cost

Table 18. Ideal Results

Process	Equipment	No.	Highest productivity [cycles/hour]	Lowest cost [USD/cycle]
Unloading	Truck	4	16.13	5.07
	Forklift	3		
Lifting	Hoist	2	14.87	9.33
	Down	3		
	Up	2		
Installation	Winch	2	9.55	1,376.29
	Up	2		
	Down	2		

6. Conclusion
6.1 Summary

Our study was motivated by a lack of feasible systems or methodologies for predicting the operational performance of the curtain wall operation, which represents a critical activity in the construction of high-rise buildings. We propose a practical system composed of simulation techniques and database systems. We developed a prototype for testing and investigating the feasibility and availability of the proposed system. Data were collected from interviews with engineers and records of curtain wall operations used in high-rise construction. Simulation models were developed based on the collected data. In addition, the productivity of various equipment combinations was predicted, and the unit cost was analyzed using productivity data. The data are standardized to minimize statistical variance. Based on the statements above, this database can function as a kind of decision-making tool which is used for the establishment of a construction operational plan prior to actual construction operations.

6.2 Significance and Contributions

We propose a methodology that can facilitate appropriate decision making for the unloading, lifting, and installing processes in a curtain wall installation based on productivity and unit cost data. Our results suggest that the proposed approach can make important theoretical and practical contributions. First, methodologies for implementing database systems, such as data generation through simulation techniques and data sorting through specific ranges of unit cost and productivity, can be beneficial to researchers interested in analytic and predictive construction methods. Second, our statistical analysis can provide researchers with objective insights into experimental construction data. Finally, practitioners can use our results for more reliable operational planning, which has generally been based only on the experience of senior personnel. In this regard, this study contributes to process management decision-making based on both the experience of engineers and on objective data.

6.3 Limitations and Future Works

For applications of the proposed methodologies and resulting systems to practical situations, large amounts of raw data collected from construction sites are required. Future researchers should consider practical applications of the proposed database system and investigate the proposed methodology by using updated data. In addition, given this study's limitations, future researchers should consider a wider range of methods for collecting data and acquiring statistical knowledge, including the Bayesian model.

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