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PRODUCTIVITY MODELING OF PRECAST CONCRETE INSTALLATION USING MULTIPLE REGRESSION ANALYSIS

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ABSTRACT

Precast concrete products are generally used to shorten project duration and provide higher quality and more sustainable construction projects. There are many factors affecting productivity in precast concrete construction sites and there is a lack of research in terms of estimation tools for prediction of precast installation times for different components that are widely used in precast projects (walls, columns, beams, and slabs). Therefore, this study was designed to study the erection of different precast panels and develop a regression model to estimate the installation times based on the selected factors (extracted from literature, interviews, and site visits) involved in different stages of installation process namely preparation, lift, and fixing activities. The results showed the appropriateness of the model to be used by site managers and general estimators for their planning purposes. This study contributes to the construction management knowledge by providing simple but effective models to predict the installation times of precast elements. Significant factors involved in each stage of precast installation were discussed and limitations and recommendations for future research were presented.

Keywords: construction productivity, precast concrete erection, productivity estimation, multiple regression analysis.

INTRODUCTION AND LITERATURE REVIEW

Since 1950's, contractors have used Precast Concrete (PC) products to meet the challenges they faced such as long construction duration and poor quality. In fact, the first large-scale use of precast panels as cladding was at Denver Hilton (Denver, Colorado, USA) project and upon successful completion, architects started to use PC elements in important building projects [5].

PC components are produced in a controlled environment in precast manufacturing companies or in the temporary precast plants which are set up near the construction sites. This provides the opportunity for PC to be properly cured and monitored by plant labor. Some of the general advantages of precast projects when compared to traditional cast-in-situ can be summarized as [1, 7, 8, 11]:

- Higher quality products due to close monitoring of the manufacturing phase.
- Cost savings in terms of mold per unit of production.
- Enhanced safety.
- Concurrent work of PC manufacturing and foundation works.
- Faster erection of building structure.
- Adverse impact of weather can be mitigated during PC manufacturing.
- Varied and high quality surface textures can be produced by specific surface treatments at the production plants.
- Environmental benefits such as reducing wastage of materials and minimizing site debris and dust.
- Achieving sustainability.

Regression analysis is generally used to find a linear relationship between a set of predictors and a dependent variable [4]. This technique has been widely used in different areas of construction management research such as cost estimation for different projects [9] and estimating project duration [4]. Productivity estimation and modeling is among those areas that have utilized Multiple Regression Analysis (MRA) to develop simple and reliable estimation models of productivity measures for different construction tasks.

The main reason to choose MRA in this study is its ability to provide a simple and clear functional form between the influencing factors (inputs) and the output from which the relationship between the input variables and the output can be easily interpreted.

RESEARCH METHODOLOGY

This study consists of two phases. First phase includes collecting the factors affecting productivity and gathering the primary data to build the regression models for precast installation. At the second phase a set of 30 data points is used to validate the developed models.

Factors affecting productivity of precast installation

Based on the site visits, a typical erection process consists of several tasks which are shown in Figure-1.

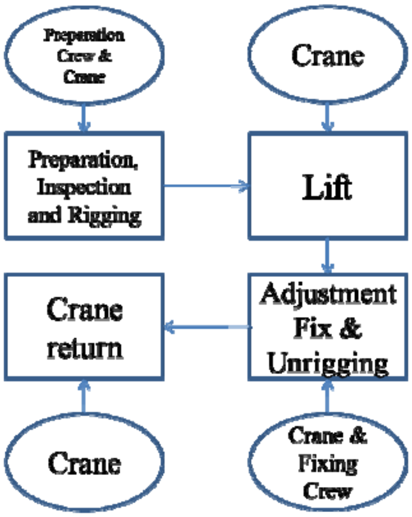

Figure-1. A typical PC erection process.

In this Figure ovals and rectangles represent resources and activities, respectively. Therefore, for a typical erection process, four major activities are as follows:

a) **Preparation, inspection, and pick-up:** This is performed by a signal man (rigger man) at the storage area. The component is quickly checked against physical damages (if any) and then the signal man will attach the crane hook to the lifting inserts on the element.
b) **Lifting:** The crane raises the component to be installed at the unloading point.
c) **Adjustment, fix, and unrigging:** The element will be adjusted and fixed at the designated location based on the drawings. Diagonal props will be used as temporary support for vertical elements.
d) **Crane return:** As soon as the crane hook is detached from the lifting inserts, crane returns for the next cycle or other lifting purposes.

Based on the above mentioned steps, total of 18 factors (Table-1) affecting the productivity of precast erection process considered in this study. Crane productivity factors (X_1- X_3, X_7- X_9, X_{17}- X_{18}) were extracted from literature [11, 12] and factors related to preparation and fixing activities were identified through site visits and observations of precast installations.

Table-1. Factors affecting precast erection productivity.

Factor	Name	Description	Coding/Unit of measurement
X_1	Weight	Component weight	Ton (t)
X_2	Area	Largest surface area of the component	Square meters (m^2)
X_3	Length	Longest length of the element	Meter (m)
X_4	Height	Component Height	Meter (m)
X_5	Storage Type	The component is stored among others or being isolated	1: Isolated 2: Among Others
X_6	Storage to Crane	Distance from component to crane center in the storage	Meter (m)
X_7	Installation to Crane	Distance from the installation point to the crane center	Meter (m)
X_8	CraneAngle	Angle between storage and installation	Degree
X_9	CraneType	Type of crane used	1: Tower Crane 2:Crawler Crane
X_{10}	Installation Type	The component is installed among others or isolated	1: Isolated 2: Among others
X_{11}	Location Type	The component is exterior or Interior	1: Exterior 2: Interior
X_{12}	Rebars	Number of rebars to fix the component (for vertical elements)	Number: 1…n
X_{13}	Lifting Inserts	Number of lifting inserts of the component	Number: 1…n
X_{14}	Props	Number of diagonal props for temporary support	Number: 1…n
X_{15}	Prop Inserts	Number of holes to be drilled for props installation	Number: 1…n
X_{16}	Fix Crew Size	Crew size in charge of precast installation	Number: 1…n
X_{17}	Elevation	Elevation of the installation point	Meter (m)
X_{18}	Shape	Component orientation (Vertical and Horizontal)	1: Vertical 2: Horizontal

Data were collected from construction sites across Singapore and Malaysia and because of the tropical weather of this region, data on weather conditions such as temperature, humidity and wind speed were not collected and included in the analysis. Crane operators have also mentioned that the hoisting speed is affected only in adverse weather conditions and for safety reasons, hoisting is stopped during rain or strong wind [2]. This point was further confirmed by the research team during site visits and data collection. As a result, including weather condition variables in the regression models may not be critical.

Data collection

Primary data for this study were collected from four construction sites across Singapore and Malaysia including residential buildings and a school project. For the data collection, the installations of 220 PC panels were observed and stopwatch was used to record the time of different activities shown in Figure-1. 190 data points were randomly selected to build the regression models and the remaining 30 cases were kept to test the model performance. Table-2 shows general characteristics of PC elements studied in this research.

Table-2. General characteristics of PC elements.

	Wall	**Column**	**Beam**	**Slab**
No. of cases	**126**	**80**	**34**	**73**
Length (m)	1.40 - 5.75	0.40 - 2.00	5.57 - 9.22	2.40 - 8.73
Width (m)	0.10 - 0.25	0.20 - 0.75	0.30 - 0.80	0.37 - 2.40
Height (m)	2.80 - 3.58	2.80 - 5.80	0.32 - 0.60	0.07 - 0.27
Weight (t)	0.95 - 7.31	1.00 - 3.50	2.06 - 5.66	0.80 - 3.09

Regression models for precast erection activities

A linear regression model in the form of following will be developed for each of the activities involved in the erection cycle time:

$$Y = B_0 + B_1 X_1 + B_2 X_2 + \cdots + B_n X_n \qquad (1)$$

The main dependent variable (Y) is the time (in minutes) required to finish the main installation activities (Preparation, Lift, and Fix). B_0 is the intercept and $B_1, B_2, \ldots, B_n$ are the coefficients of the relationship. X_1, X_2, …, X_n are the factors described in Table-1 and data for these factors were collected through observations and from the relevant drawings such as precast shop drawings, site storage drawings, and level layout plans.

To build the model and estimate the coefficients of the regression model, the ordinary least squares (OLS) method was used using SPSS V.17. To provide better estimates and to find the significant variables, both “enter” and “stepwise” methods were considered. The difference between these two methods is that in the latter, the variables are entered for examination at each step for entry and removal analysis. However, in the former method, all of the variables are entered in a single step and the predicted model will usually include all of the variables (unless a variable is below the tolerance criterion - 0.0001) [2]. Selection between ‘‘enter’’ and ‘‘stepwise’’ models is based on values of t-statistic, F-statistic, and minimization of mulitcollinearity. Usually stepwise method provides robust models by including most of the significant factors.

Regression model for preparation activities

Preparation activities are the first stage in the cycle time of precast installation. Storage type (X_5), length (X_3), area (X_2), weight (X_1), height of the component (X_4), and number of lifting inserts (X_{13}) are the relevant factors to be considered in the regression analysis of preparation activities. The results for both “enter” and “stepwise” methods are shown in Table-3.

Table-3. Regression analysis for preparation activities.

	R	R Square	Adj. R Square	Std. Error	F	Sig. ANOVA
Enter	.670	.449	.431	.582	29.016	0.000
Stepwise	.666	.444	.435	.580	48.674	0.000
Variable (Enter)	**B**	**Std. Error**	**Beta**	**t**	**Sig.**	**VIF**
(Constant)	-.576	.229		-2.517	.013	
Storage Type	1.072	.102	.667	10.538	.000	1.308
Weight	-.019	.046	-.034	-.411	.682	2.288
Length	.080	.020	.274	3.915	.000	1.603
Area	.031	.017	.155	1.817	.071	2.368
Height	.085	.070	.170	1.210	.228	6.434
Lift Inserts	.011	.070	.011	.153	.878	1.534
Variable (Stepwise)	**B**	**Std. Error**	**Beta**	**t**	**Sig.**	**VIF**
(Constant)	-.565	.172		-3.293	.001	
Storage Type	1.062	.100	.662	10.628	.000	1.275
Length	.080	.020	.274	3.982	.000	1.559
Area	.028	.013	.137	2.138	.034	1.351

Table-3 shows that 44.9 percent (R-square of the enter method) of the variation in the preparation time can be explained by the selected factors. However, some p-values are more than 0.05 that is an indication of possible insignificant predictors. Therefore, the stepwise method was used and the results showed that 44.4 percent (with p-value from ANOVA Table less than 0.05) of the variation in preparation time can be explained by storage type (X_5), length (X_3), and area (X_2). All p-values are less than 0.05 and no significant multicollinearity can be considered (all VIF values are less than 5). As a result, the final regression model for the preparation time is:

$$Y_P = -0.565 + 1.062\,X_5 + 0.08\,X_3 + 0.028\,X_2 \qquad (2)$$

Y_P is the estimated preparation time and the model implies that with one unit increase in length and area of the element, the preparation time will increase by 0.08 and 0.028 minutes, respectively. Additionally, when the storage type of a component changes from being isolated to be stored among others, the preparation time will increase by 1.062 minutes. Figure-2 confirms this point by depicting that preparation of isolated components is easier when compared to those among others.

Figure-2. Preparation of elements in different storage conditions.

Regression model for hoisting time (Lift)

The relevant factors to build the regression model for hoisting time are: elevation (X_{17}), area of the load (X_2), component orientation (X_{18}), crane angle (X_8), distance from installation to crane (X_7), crane type (X_9), component weight (X_1), distance from storage to crane (X_6), and component length (X_3). These factors were extracted from the relevant literature [2, 3, 10]and confirmed to be important through site visits and interviews. The analysis and results of the regression models for enter and stepwise methods are shown in Table-4.

Table-4. Regression analysis for hoisting times (lift).

	R	R Square	Adj. R Square	Std. Error	F	Sig. ANOVA
Enter	.815	.664	.647	.710	39.453	0.000
Stepwise	.806	.650	.638	.719	56.623	0.000
Variable (Enter)	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	-1.913	.601		-3.182	.002	
Orientation	-1.086	.253	-.443	-4.285	.000	5.712
Storage to Crane	.025	.008	.260	3.239	.001	3.458
Installation to Crane	.016	.009	.082	1.783	.076	1.125
Crane Angle	.010	.001	.514	10.138	.000	1.376
Crane Type	1.857	.193	.776	9.618	.000	3.480
Length	-.035	.050	-.078	-.706	.481	6.517
Area	.041	.020	.129	1.993	.048	2.252
Weight	.089	.070	.105	1.259	.210	3.755
Elevation	.037	.005	.516	7.287	.000	2.685
Variable (Stepwise)	B	Std. Error	Beta	t	Sig.	VIF
(Constant)	-1.418	.485		-2.924	.004	
Crane Angle	.011	.001	.527	10.647	.000	1.279
Storage to Crane	.024	.008	.246	3.083	.002	3.334
Orientation	-1.155	.128	-.471	-9.034	.000	1.419
Crane Type	1.856	.186	.775	9.992	.000	3.146
Elevation	.037	.005	.513	7.352	.000	2.544
Weight	.144	.043	.172	3.319	.001	1.397

The analysis of the stepwise method shows that 65 percent of the variation in the lifting time can be explained by crane angle (X_8), distance from storage to crane (X_6), orientation of the load (X_{18}), crane type (X_9), elevation (X_{17}), and weight (X_1). Therefore, the regression model for the lifting time can be written as:

$$Y_L = -1.418 + 0.011\,X_8 + 0.024\,X_6 - 1.155\,X_{18} + 1.856\,X_9 + 0.037\,X_{17} + 0.144\,X_1 \quad (3)$$

Y_L is the estimated lift time and the model shows that with one unit increase in crane angle, distance from storage to crane, elevation of the installation point, and component weight, lifting time increases by 0.011, 0.024, 0.037, and 0.144 minutes, respectively. Additionally, when the crane type changes from tower crane to the crawler crane, there is an increase of 1.856 minutes in the lifting time. There is an average decrease of 1.155 minutes in the lifting time of horizontal components when compared to vertical elements.

From the significant factors of preparation and hoisting times, it can be seen that just-in-time (JIT) deliveries of PC elements will directly improve the overall productivity of erection process. This is because the components can be picked up from the trailers (elements can be considered as isolated in equation 2) and also the trailer can be positioned near the crane in such a way that the distance between the elements and crane center as well as crane angular movement are minimized (equation 3). Furthermore, double handling, space constraints, and traffic congestion at the worksite can be alleviated using JIT delivery system [6].

Regression model for fixing activities

In the regression model for fixing activities, the following predictors should be considered: area (X_2), weight (X_1), component height (X_4), length (X_3), location type (X_{11}), number of hooks (X_{13}), number of rebars (X_{12}), number of props (X_{14}), number of inserts for props installation (X_{15}), installation type (X_{10}), and fixing crew size (X_{16}). There might be a concern that number of number of inserts for props installation (X_{15}) might be related to number of props (X_{14}). In the other words, for each prop, at least 2 inserts must be available (one on the element and the other on the below slab). Our observations showed that in some construction sites (most of the public housing sites) they already indicated the inserts on the slab before concrete pouring. Therefore, no drilling will be required on the slab. This is one of the best practices that is used in Singapore public housing projects which increases the productivity by eliminating the drilling time. However, some construction sites do not use this technique (drilling is required). On the other side, there are readily available inserts on the components to support the props. However, sometimes, those inserts are clotted and cannot be used and therefore, crew are required to drill on the component as well. This means that number of inserts to be used for props installation will be varied based on the project conditions.

It should be mentioned that number of props not only shows the total number of props to support the element, but also indicates the orientation of the element as well. In the other words, if number of props equals zero, the component is a horizontal element (either beam or slab). Props must be necessarily used to support vertical components (columns and walls) which indicates that X_{14} (number of props) equals or greater than one for all of the vertical elements. The results of the regression analysis for fixing activities are shown in Table-5.

Table-5. Regression analysis for fixing activities.

	R	**R Square**	**Adj. R Square**	**Std. Error**	**F**	**Sig. ANOVA**
Enter	.906	.821	.810	3.034	72.895	.000
Stepwise	.897	.805	.801	3.101	188.300	.000
Variable (Enter)	**B**	**Std. Error**	**Beta**	**t**	**Sig.**	**VIF**
(Constant)	.304	2.227		.136	.892	
Location Type	-2.641	.548	-.190	-4.821	.000	1.516
Area	-.142	.104	-.078	-1.367	.173	3.182
Weight	2.017	.333	.415	6.060	.000	4.582
Length	-.192	.228	-.073	-.843	.400	7.337
Lifting Inserts	.708	.452	.078	1.564	.120	2.403
Joints	-.017	.173	-.007	-.098	.922	5.000
Props	1.064	.372	.234	2.857	.005	6.535
Prop Inserts	1.281	.234	.346	5.486	.000	3.889
Height	.520	.460	.115	1.130	.260	10.075
Install Type	.069	.547	.005	.127	.899	1.518
Fix Crew Size	.795	.416	.080	1.914	.057	1.699
Variable (Stepwise)	**B**	**Std. Error**	**Beta**	**t**	**Sig.**	**VIF**
(Constant)	3.534	1.033		3.419	.001	
Weight	1.477	.173	.304	8.527	.000	1.187
Location Type	-2.415	.513	-.174	-4.704	.000	1.274
Prop Inserts	1.551	.137	.419	11.322	.000	1.282
Props	1.780	.166	.391	10.733	.000	1.242

The analysis of stepwise regression implies that 80.5 percent of variation in the fixing time can be explained by weight (X_1), location type (X_{11}), number of prop inserts (X_{15}), and number of props (X_{14}). The regression model for fixing time can be expressed as:

$$Y_F = 3.534 + 1.477\,X_1 - 2.415\,X_{11} + 1.551\,X_{15} + 1.78\,X_{14} \quad (4)$$

Y_F is the estimated fixing time (in minutes) and based on the predictors' coefficients, as number of prop inserts, number of props, and component weight increase by one unit, the fixing time increases by 1.551, 1.780, and 1.477 minutes respectively. Additionally, when the location type of a component changes from exterior to interior, the fixing time decreases by 2.415 minutes. This is mainly because, fixing of interior elements are easier due to more available space for fixing activities. Also, to install some external vertical elements the workers are required to do grouting and put backer rod in order to make the joints waterproof. This will increase the fixing time respectively. Note that Table-5 shows that fixing crew size was not a significant factor for estimation of fixing times. This is because the crew size is usually fixed for precast activities (1 rigger man at the storage area, 1 rigger man at the installation point with 3-4 general workers). However, in some special cases for big vertical elements (structural walls or big facades), the crew in charge of grouting activities (1-2 workers) may join to help the fixing crew.

After the component is properly fixed, the crane can return to begin the next cycle. However, observations showed that due to other lifting purposes, the crane may not directly go to the storage area right after the installation of the previous element. Therefore, this study didn't analyze the crane return time. Based on the collected data, an average of 2 minutes can be considered for the crane return time. If a more accurate model is needed, the readers should refer to the available literature on crane productivity studies [2, 3, 10].

Validation of the installation regression model

The regression model to estimate the installation time (excluding crane return time) for different PC elementsis the sum of preparation, lift, and fixing activities:

$$Y_I = Y_P + Y_L + Y_F \tag{5}$$

Y_I is the estimated installation time and Y_P, Y_L, and $Y_F$are the predicted time for preparation, lift, and fixing activities that are calculated from Eq. 2 - 4. As mentioned earlier, a set of 30 cases were used to verify the predictive ability of the model and mean absolute error (MAE), mean absolute percentage error (MAPE), and mean square error (MSE) were calculated by:

$$MAE = \frac{\sum_{1}^{n} |Y_I - Y_A|}{n} \tag{6}$$

$$MAPE = \left(\sum_{1}^{n} \frac{\left[100 * \frac{|Y_I - Y_A|}{Y_A}\right)}{n}\right] \tag{7}$$

$$MSE = \frac{\sum_{1}^{n} [(Y]_I - Y_A)^2}{n} \tag{8}$$

Y_A is the actual installation time collected from the sites and n is the number of cases (n = 30). As a result, errors were calculated and are shown in Table-6.

Table-6. Error estimates.

MAE	MAPE	MSE	Min. abs. error	Max. abs. error
2.08	14.74	8.86	0.18	9.18

Table-6 shows that on average, predictions from the developed model will be only 14.74 percent higher or lower than the actual data with an average of 2.08 minutes error estimate (prediction accuracy of the model is 85.26 percent). This indicates that the model fits the actual data and looks valid. Figure-3 shows the actual and predicted data for test cases of preliminary validation.

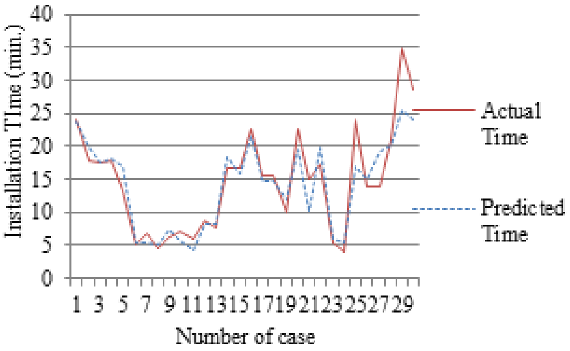

Figure-3. Comparison of the actual and predicted installation times.

Figure-4 illustrates the accuracy of the developed regression model through depicting the correlation between predicted and actual installation times. It can be seen that the model can effectively estimate PC erection time for test cases and since these cases have not been used in the model building, it can be concluded that the model is generalizable.

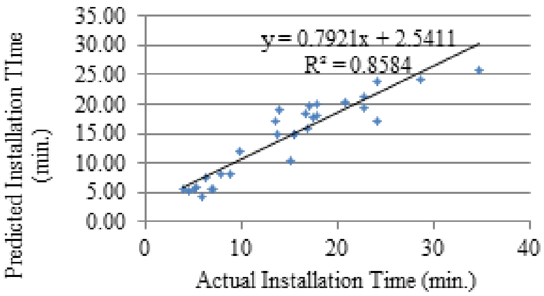

Figure-4. Correlation between actual and predicted installation times.

CONCLUSIONS

In this study, installation of 220 precast concrete panels were used to build a model to predict the erection time of different precast elements including structural/non-structural walls, columns, beams, and slabs. The erection model was developed by three different regression models for preparation, lift, and fixing activities. Both enter and stepwise regression techniques were utilized in model developments and the significant factors to build the models were identified using stepwise regression analysis as follows: storage type (isolated or among others), length, and area for preparation activities; crane angular movement between installation and storage points, distance from the element to the crane at the storage area, orientation of the element (vertical/horizontal), type of the crane used (tower crane/crawler crane), elevation of the installation point, and weight for lifting time; weight, location type (exterior/interior), number of prop inserts to be used for props installation, and number of diagonal props for fixing activities.

30 cases were used to test the final model and the predictive ability of the model was found to be 85.26 percent. The main objective of this research was to develop simple but effective models to estimate the precast installation times. The results showed high accuracy and therefore, appropriateness of the model to be used by construction managers and general estimators for their scheduling purposes.

Other precast elements such as balconies, staircases, and ducts can be studied in future research. Additionally, more prediction tools (e.g. Artificial Neural Networks and Simulation) will be used and the estimation performance will be compared among those techniques to choose the best possible option from which a computer program will be developed to facilitate data entry, analysis, and report generation for researchers and practitioners.

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