ABSTRACT:
Assessing productivity, cost, and delays are essential to manage any construction operation, particularly the concrete batch plant operation (CBP). This paper focuses on assessing the above-mentioned items for CBP operations using stochastic mathematical models. It aims at (1) identifying the potential sources of delay in concrete batch plant operation; (2) assessing their influence on production, efficiency, time, and cost; and (3) determining each factor share in inflating the CBP concrete unit price. Stochastic mathematical models were designated to assess various delay types and their effect on production efficiency, cost, and time. Data were collected from a CBP site to verify the designated models. The results show that management condition has the highest probability of occurrence, delay percent, and relative delay percent. It is also concluded that mechanical delays has a high delay percent. These delays increase the CBP expenses by $2.59 for each cubic meter.

INTRODUCTION
The United States RMC produced 242 million cubic yards of concrete (184 million cubic meters) in 1990, which increased to 395 million cubic yards (300 million cubic meters) in 2000
On average, the estimated revenue of the RMC industry was around $25 billion in 2000. Two situations govern the selection of RMC for a particular project: (1) the site is congested, which is the case for residential building sites where there is little room for mixing concrete, and storing cement and aggregate; (2) the location of casting concrete is continually moving (non-stationary). The concrete can be mixed in a batch plant offsite (RMC) or in an onsite batch plant (OBP) and then transported by transit mixers (NRMCA, 1995; Peurify et al., 1996; Strehlow, 1973; Strehlow, 1974; Camillo, 1996; Haney, 1985; and Mininger, 1969).

Optimizing the concrete batch plant (CBP) operation, whether it is RMC or OBP, will lead to appreciable savings in such an important element of the construction industry. Consequently, special attention has to be paid to this sector.

A model is a representation of a real-world situation and provides a framework within which a given system can be investigated and analyzed. Models contain and reflect data that, when interpreted according to certain rules or conventions, provide information that supports the decision-making process (Halpin, D. W. and Riggs, L. S., 1992). The precision with which these models reflect the real world varies widely (Zayed and Halpin, 2001). Previous studies designated several models to assess CBP productivity, cost and quality. Anson and Wang (1998) developed a research to assess productivity, resource availability and utilization, and the factors that affected placing rates, pour size, type of pour, and supply of concrete. It also provided benchmarks for Hong Kong building industry. Alhozaimy and Al-Negheimish (1999) designated a quality scheme for RMC in Riyadh, Saudia Arabia. This research encountered the major difficulties and challenges faced the quality scheme in its development as well as implementation stages. Zayed and Halpin (2001) designated a simulation model to assess the CBP productivity and cost considering one-plant-one-site CBP system. It added one more dimension to price out
the CBP concrete unit: transporting distance. Lu et al. (2003) developed a simulation model and software for the RMC that studied the CBP for one-plant-multi-site RMC system. Zayed and Minkarah (in press) developed an optimization model for the CBP to optimize resource and space utilization. These studies did not consider the delays and their effect on the production of the CBP, which will be the scope of current study.

Stochastic mathematical models were designated to assess different delays and their effect on production efficiency, cost, and time. The assessment process considers potential delay factors that affect the concrete batch plant production, such as delays in the construction site; delays in the batch plant site; delays due to traffic conditions; and delays due to road conditions. Therefore, the price of a concrete cubic yard, which is produced by the CBP, is affected by the aforementioned factors. Common practice prices out the concrete based upon materials price plus overhead and profit without considering the transporting distance, and delays.

Current study capitalizes on Zayed and Halpin (2001) previous research that added the transporting distance as a dimension in the CBP concrete unit price. To enhance the productivity and cost estimation per unit, current study adds one more dimension to price out the CBP concrete unit: delays in plant and construction sites. Therefore, this study focuses on: (1) identifying the potential sources of delay in concrete batch plant operation; (2) assessing their influence on production, efficiency, time, and cost; and (3) determining each factor share in inflating the CBP concrete unit price.

**POTENTIAL CBP SOURCES OF DEALY**

Tremendous factors influence the CBP production; however some of these factors are manageable and some of them are not. Anson and Wang (1998) and Zayed and Halpin (2001)
mentioned several productivity factors: placing method, organizational and management factors, labor crew skills, pumping spaces, site congestion, site access conditions, client characteristics, number of truck mixers available, structure element to be placed, work volume required, weather conditions, materials delivery system, and mechanical problems. The aforementioned factors share with different percentages in reducing productivity and/or increasing delays. Consequently, current study categorizes delays into two major categories. First, Uncontrolled Delays (UD), delays due to factors that are out of plant management control. The second category includes, Controlled Delays (CD), delays due to factors that can be controlled by plant management.

**Uncontrolled Delays (UD)**

The major elements of the UD are as follows:

1- **No work**: there is no work available for the plant (low demand).

2- **Concrete pouring method**: delays due to the method that is used to pour concrete and pumping available spaces.

3- **Weather conditions**: delays due to the conditions of weather.

**Controlled Delays (CD)**

The major elements of the CD are as follows:

4- **Management conditions**: delays because of number of truck mixers is not convenient, pouring crew skills, and site conditions.

5- **Mechanical**: delays due to mechanical problems.

6- **Cement delivery**: delays due to cement delivery problems.

7- **Aggregates delivery**: delays due to aggregates delivery problems.
DEVELOPMENT OF THE CBP STOCHASTIC MODELS

The CBP expenses per unit can be broken down into batch plant expenses (BPE) and transporting expenses (TE). The BPE includes the expenses of batch plant and its service equipments and tools; however, the TE includes truck mixer expenses. Peurifoy et al. (2002) divided the total expenses of any construction equipment into ownership expenses (OE) and operating expenses (PE). Since the CBP and its truck mixers are both equipments, it is better to categorize their expenses into OE and PE. The OE includes depreciation; maintenance and repair (M&R); and spare parts and tools. The PE includes fuel, grease, oil, wages, salaries, and others. Accordingly, the total equipment expenses can be determined using the following model (1):

\[
\text{Total Equipment Expenses (TEE)} = \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} \text{ ($/m^3$)}
\]  

(1)

To determine the probability of occurrence for various delay types, the number of occurrence is divided by the total number of observations for this particular type. Model (2) shows this application as follows:

\[
\text{Probability } (P_{kh}) = \frac{t}{N} \quad (\%) 
\]  

(2)

But the challenge that faces this straightforward application is the weight of each occurrence (delay time). The delay time is not equal for each time of occurrence; therefore, this straightforward application to determine probability is not sufficient. In other words, each time a delay consumed a different time from the previous occurrence. For example, cement delivery delay takes 20, 60, and 90 minutes in the 1st, 2nd, and 3rd occurrences, respectively. Since determining only the probability of occurrence is not sufficient, the weight (delay Time) of each occurrence should be considered using the weighted average technique to calculate the delay percent for a specific delay type. Based upon the previous discussion, the delay percent can be determined using model (3) as follows:
Delays Percent (DP) = \left[ \sum_{k=1}^{r} \sum_{h=1}^{l} D_{kh} \right] \times \frac{P_{kh}}{Z} \% \quad (3)

Production efficiency for the CBP can be assessed using the following stochastic model (4):

Efficiency = 100 - DP \% \quad (4)

By substituting the value of DP from model (3) in (4), then, model (5) is concluded as follows:

Efficiency = 100 - \left[ \sum_{k=1}^{r} \sum_{h=1}^{l} D_{kh} \right] \times \frac{P_{kh}}{Z} \% \quad (5)

The expenses are usually increased due to delays; therefore, the effective and extra expenses can be calculated in the stochastic models (6), (7), (8), & (9) as follows:

Effective Expenses (EE) = \frac{100 \times \text{Total Expenses ($/m^3)}}{\text{Efficiency} \%} \quad (6)

\[ EE = 100 \times \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} \times \left( 100 - \left[ \sum_{k=1}^{r} \sum_{h=1}^{l} D_{kh} \right] \times \frac{P_{kh}}{Z} \right) \% \quad ($/m^3) \quad (6) \]

CASE STUDY

A concrete batch plant, in Lafayette, Indiana, is selected to apply the designated models and verify their robustness in assessing the delays and their influence on efficiency, cost, and time. Data have been collected from the CBP site during five months period. Several techniques have been used to collect data: (1) CBP daily reports; (2) interview with CBP management using site visits and telephone calls; and (3) direct data collection forms that are filled during the CBP site visits. Data have been processed and analyzed statistically to implement the designated models.
RESULTS ANALYSIS

Data were collected using different data collection tools from the CBP. Different delays were recorded during the data collection period. These delays are discussed in details in the earlier sections of this paper. Probability of occurrence for each delay type is determined using model (2) as shown in Figure 1. It shows that the delay due to management conditions has the highest probability of 38%. However, the delay due to mechanical problems is sorted second highest where it has a probability of 20%. On the other hand, delay due to pouring method has the lowest probability of occurrence (0.03).

As mentioned earlier in this paper, pure probability calculation is not sufficient to indicate the delay effect because each time a delay occur consume different duration from the previous. Therefore, the analysis of different delays using model (3) is shown in Table 1. The percentage of each delay type is determined based upon the weighted average technique as shown in model (3). The summation of all delays represents 14.7% of the CPB operation time. The results show that the CPB is working with an efficiency of 85.3% (using model (5)) as shown in Figure 3. Management delay has the highest percent of 9.17%; however, the delay because aggregates are not available is 0.48%. Uncontrolled delays represent 2.16% of CPB operation time and controlled delays represent 12.54%. Based upon this discussion, good management can reduce delays by 85.3% (controlled delays) to enhance the efficiency to be 97.84%.

The relative percent for each delay factor is shown in Figure 2. Delays due to management conditions rank first with a relative delay percent of 62.39%. Mechanical repair ranks second with a relative delay percent of 14.56%. Other factors range from 3-7% relative to other delay factors. It is very clear that the controlled delays have the major delay share, which
can be improved by enhancing the management tools and measurement for the CBP. As shown in Figure 3, these delays increase the total CBP expenses from $15.04/m³ to $17.63/m³. Consequently, $2.59 is added to each cubic meter because of inefficient work or management. The CBP management has to change its way of operating their plant to reduce these delays and their side effects on the CBP expenses.

CONCLUSION

Factors that affect delay in the CBP operation are identified and analyzed. Based upon these identified factors, several cost management models have been developed to assess CBP efficiency and effective expenses. Current study collected data from a CBP site to verify the designated models. They have been applied to the case study; however, the results show that management condition has the highest probability of occurrence, delay percent, and relative delay percent. It is also concluded that mechanical delays has a high delay percent. These delays increase the CBP expenses by $2.59 for each cubic meter.

APPENDIX I. NOTATIONS

\[ C_{ij} = \text{equipment expenses per cubic meter of concrete for } i \text{ expenses categories and their } j \text{ expenses sub-categories} (\$/m^3). \]
\[ n = \text{maximum number of expenses breakdown types.} \]
\[ m = \text{maximum number of expenses sub-categories and their elements.} \]
\[ t = \text{total number of occurrences for each delay type.} \]
\[ N = \text{total number of observations during the study period.} \]
\[ D_{kh} = \text{delays percent for } k \text{ delay types and } h \text{ elements of different types.} \]
\[ P_{kh} = \text{probability of delay type } k \text{ and its elements } h. \]
\[ r = \text{the maximum number of delay types.} \]
\[ l = \text{the maximum number of elements in each delay type.} \]
\[ Z = \text{number of plant sites.} \]

**Subscripts and Superscripts**

\[ i = \text{expenses breakdown types BPE or TE.} \]
\[ j = \text{expenses sub-categories OE and PE and their elements.} \]
\[ k \] = number of delay types UD and CD.

\[ h \] = number of delay types elements.

**APPENDIX II. REFERENCES**


Figure 1: Delays Probabilities

- Mechanical: 20%
- No work: 12%
- Weather: 7%
- Management: 38%
- Aggregates Delivery: 9%
- Cement Delivery: 11%
- Pouring Method: 3%

Figure 2: Relative Percent for Delay Factors

- Management: 62.39%
- Weather: 3.53%
- Pouring: 4.28%
- No work: 6.91%
- Aggregates Delivery: 9%
- Cement Delivery: 11%
- Cement: 5.03%
- Manag.: 14.56%
- Agg.: 3.30%
Figure 3: CBP Efficiency, Total Expenses, and Effective Expenses

Table 1: CBP Delays Analysis

<table>
<thead>
<tr>
<th>Plant No.</th>
<th>Total Study Time (hr)</th>
<th>Uncontrolled Delays Time and Percent</th>
<th>Controlled Delays Time and Percent</th>
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<td></td>
<td>No work Delay</td>
<td>Pouring Delay</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time (hr)</td>
<td>Time (hr)</td>
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<td>1429</td>
<td>121</td>
<td>8.5</td>
</tr>
<tr>
<td>Total</td>
<td>1429</td>
<td>121</td>
<td><strong>8.5</strong></td>
</tr>
<tr>
<td>Probability</td>
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<td>0.03</td>
<td>0.07</td>
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<tr>
<td>Delay Percent</td>
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<td><strong>0.63</strong></td>
<td><strong>0.52</strong></td>
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