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Canadian Journal of Civil Engineering; Aug. 2006; 33, 8; SciTech Premium Collection
pg. 1065

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Tarek M. Zayed and Ibrahim A. Nosair

Abstract: Assessing productivity, cost, and delays are essential to manage any construction operation, particularly the concrete batch plant (CBP) operation. This paper focuses on assessing the above-mentioned items for the CBP using stochastic mathematical models. It aims at (*i*) identifying the potential sources of delay in the CBP operation; (*ii*) assessing their influence on production, efficiency, time, and cost; and (*iii*) determining each factor share in inflating the CBP concrete unit expense. Stochastic mathematical models were designed to accomplish the aforementioned objectives. Data were collected from five CBP sites in Indiana, USA, to implement and verify the designed models. Results show that delays due to management conditions have the highest probability of occurrence (0.43), expected value of delay percent (62.54% out of total delays), and relative delay percent. The expected value of efficiency for all plants is 86.53%; however, the average total expense is US\$15.56/m^3 (all currency are in US\$). In addition, the expected value of effective expenses (EE) is \$18.03/m^3, resulting in extra expenses (XE) of \$2.47/m^3. This research is relevant to both industry practitioners and researchers. It develops models to determine the effect of delays on concrete unit cost. They are also beneficial to the CBP management.

Key words: concrete batch plant, delays, management conditions, cost models, cost management, stochastic mathematical models.

Résumé : L'évaluation de la productivité, des coûts et des délais est essentielle pour gérer toute opération de construction, particulièrement les opérations des centrales à béton (« concrete batch plant (CBP) »). Le présent article porte sur l'évaluation des points ci-dessus pour les CBP par l'utilisation de modèles mathématiques stochastiques. Son objectif est de (*i*) identifier les sources potentielles de délai dans les opérations des CBP; (*ii*) évaluer leur influence sur la production, l'efficacité, le temps et le coût; et (*iii*) déterminer la part de chaque facteur dans l'augmentation des coûts de l'unité de béton de la CBP. Les modèles mathématiques stochastiques ont été conçus pour atteindre ces objectifs. Des données ont été colligées de cinq sites CBP en Indiana, aux É.-U., afin d'implanter et de vérifier les modèles conçus. Les résultats montrent que les délais causés par les conditions de gestion représentent la plus forte probabilité d'occurrence (0,43), la valeur prévue du pourcentage de délai (62,54 % de tous les délais) et le pourcentage de délai relatif. La valeur prévue d'efficacité de toutes les centrales est de 86,53 %; cependant, le coût moyen total est de 15,56 \$ US/m^3. De plus, la valeur prévue des coûts effectifs (« effective expenses (EE) ») est de 18,03 \$/m^3 entraînant des coûts supplémentaires (« extra expenses (XE) ») de 2,47 \$/m^3. La présente recherche est appropriée pour les intervenants et les chercheurs de l'industrie. Elle développe des modèles pour déterminer l'effet des délais sur le coût unitaire du béton. Ces modèles peuvent également profiter aux gestionnaires des CBP.

Mots clés : centrale à béton, délais, conditions de gestion, modèles de coûts, gestion des coûts, modèles mathématiques stochastiques.

[Traduit par la Rédaction]

Introduction

The United States offsite ready mixed concrete industry (RMC) produced 184 × 10^6 m^3 (242 × 10^6 cubic yards) of concrete in 1990, which increased to 300 × 10^6 m^3 (395 × 10^6 cubic yards) in 2000 (Zayed and Minkarah 2004). This work volume generated an estimated revenue of US\$25 billion in 2000 for the RMC industry. Therefore, studying the RMC process and its delays becomes essential. Two situations govern the selection of RMC for a particular project: (*i*) the construction site is congested, which is the case for residential building sites where there is little room for mixing concrete or storing cement and aggregate; (*ii*) the location of casting concrete is continually moving

Received 21 February 2005. Revision accepted 6 March 2006. Published on the NRC Research Press Web site at http://cjce.nrc.ca on 23 October 2006.

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Written discussion of this article is welcome and will be received by the Editor until 31 December 2006.

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doi:10.1139/L06-051

(nonstationary), such as in highway construction. 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; Peurifoy et al. 2002; Strehlow 1973; Strehlow 1974; Camillo 1996; Alhozaimy and Al-Negheimish 1999; Haney 1985; Mininger 1969). The OBP is installed inside a specific project to deliver concrete only to this project. Usually, this kind of project needs a large volume of concrete, such as highways, dams, canals, water and sewer treatment plants. The RMC is used to sell concrete to different projects. Optimizing concrete batch plant (CBP) operation, whether RMC or OBP, will lead to appreciable savings in such an important element of the construction industry (Zayed and Halpin 2001).

Previous studies designed several models to assess CBP productivity, cost, and quality. Anson and Wang (1998) assessed productivity, resource availability, and utilization for CBPs. They also studied the factors that affect placing rates, size, type, and methods of concrete supply. The study provided benchmarks for the Hong Kong building industry. A simulation model to assess the CBP productivity and cost considering a one-plant-one-site CBP system was designed by Zayed and Halpin (2001). 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 a one-plant-multi-site RMC system. Zayed and Minkarah (2004) developed an optimization model for the CBP to optimize resource and space utilization. These studies did not consider delays (idle time) and their effect on production of the CBP, which will be the scope of this study.

Stochastic mathematical models were used to analyze the CBP operation. 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 and Riggs 1992). The precision with which these models reflect the real world varies widely (Zayed and Halpin 2001). The CBP delay models were designed to assess different delays and their effect on production efficiency, cost, and time. The assessment process considers potential delay factors that affect the CBP production, such as delays on the construction site, at the batch plant site, due to traffic conditions, and due to road conditions. Therefore, the price of 1 m^3 of concrete produced by the CBP is affected by the aforementioned factors. Common practice prices out concrete based upon materials expenses plus overhead and profit without considering the transporting distance and delays. This study capitalizes on previous research by Zayed and Halpin (2001), which added transporting distance as a dimension in the cost of CBP concrete. To enhance productivity and cost estimation per unit, this study adds one more dimension to analyze the cost of RMC concrete unit: delays in both the CBP and construction site. Therefore, this study focuses on (*a*) identifying the potential sources of delay in the CBP operation; (*b*) assessing their influence on production, efficiency, time, and cost; and (*c*) determining each factor share in inflating the CBP concrete unit cost.

Potential concrete batch plant sources of delay (idle time)

Many factors influence CBP production; however, some of these factors are manageable and some of them are not. Anson and Wang (1998) and Zayed and Halpin (2001) reported many productivity factors: placing method, organization and management, 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 might cause delays in the CBP operation that result in low production. They share different percentages in reducing productivity and (or) increasing delays. This research presumes that all factors that reduce productivity will increase delays (i.e., productivity is inversely related to delays). Based upon the previous discussion, the current study categorizes delays into two major categories: uncontrolled delays (UD) and controlled delays (CD). The UD occur because of factors that are out of the CBP management control. The second category, CD, are due to factors that can be controlled by the CBP management. To facilitate collecting and analyzing data, this study considers only the main factors in each category. The UD and CD factors are recognized and listed based on CBP practitioners, as follows:

(*i*) 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 the available spaces for truck mixers beside the pump; (3) weather conditions: delays due to the conditions of weather.

(*ii*) controlled delays (CD) — The major elements of the CD are as follows:

(1) management conditions: delays because of insufficient number of truck mixers, pouring crew skills, and site conditions; (2) mechanical: delays due to mechanical problems; (3) cement delivery: delays due to cement delivery problems; (4) aggregates delivery: delays due to aggregates delivery problems

Development of the concrete batch plant cost, delays, and efficiency stochastic models

The CBP expenses per unit can be broken down into batch plant expenses (BPE) and transporting expenses (TE). The BPE include the expenses of the batch plant in addition to those relating to its service equipment and tools. 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 equipment, it is better to categorize their expenses into OE and PE. The OE includes depreciation, maintenance and repair, and spare parts and tools. The PE includes fuel, grease, oil, wages, salaries, and others. Accordingly, the total equipment expenses (TEE) can be determined using the following equation:

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

Where C_{ij} is the equipment expenses per cubic metre of concrete for i expenses categories and their j expenses subcategories ($/m^3), n is the maximum number of expenses breakdown types, m is the maximum number of expenses subcategories and their elements, i is the expenses breakdown types BPE or TE, and j is the expenses subcategories OE and PE and their elements.

To determine probability of occurrence for each delay type, P_{kh}, its number of occurrences is divided by the total number of observations. Equation [2] shows this application as follows:

$$[2]\qquad P_{kh} = t_{kh}/N$$

where t_{kh} is the total number of occurrences for each delay type, N is the total number of observations during the study period, k is the number of delay types (UD and CD), and h is the number of elements of the delay type.

The challenge that faces this straightforward application is the weight of each occurrence (delay duration). Delay duration is not equal for each time of occurrence; therefore, this straightforward application to determine probability is not sufficient. In other words, each delay inspired a different duration from the previous occurrence. For example, cement delivery delay takes 20, 60, and 90 min in the first, second, and third occurrences, respectively. Therefore, the amount of delay (duration) of each occurrence should be considered using the percent of delay duration to calculate the delay value for a specific delay type. For example, if the above cement delivery delays occur on three different days of 8 (480 min) working hours, then the percent of delay duration for each delay will be 20/480 = 4.17%, 60/480 = 12.5%, and 90/480 = 18.75%, respectively. Hence, the average percent of delay duration for cement delivery is (4.17 + 12.5 + 18.75)/3 = 11.80%. The delay value for each type of delay is represented in this research by "delay percent", which accommodates its probability of occurrence and the average percent of delay duration. Therefore, the delay percent for each individual type of delay can be calculated as follows:

Delay percent for each type = probability of occurrence × average percent of delay duration

Based on the previous discussion, total plant delay percent (DP) can be determined using stochastic eq. [3] as follows:

Total plant delays percent = Σ delay percents of individual delay types

$$[3]\qquad \text{Total Plant Delays Percent} = \sum_{k=1}^{r}\sum_{h=1}^{l} W_{kh}P_{kh}\ (\%)$$

where W_{kh} is the percent of delay duration for k delay types and h elements of different types, P_{kh} is the probability of delay type k and its elements h, r is the maximum number of delay types, and l is the maximum number of elements in each delay type.

Production efficiency for the CBP can be assessed using the following eq. [4]:

$$[4]\qquad \text{Efficiency} = 100 - \text{DP}\ (\%)$$

The value of DP from eq. [3] is substituted into eq. [4] to generate eq. [5] as follows:

$$[5]\qquad \text{Efficiency} = 100 - \sum_{k=1}^{r}\sum_{h=1}^{l} W_{kh}P_{kh}\ (\%)$$

The expenses are usually increased because of delays. Therefore, the effective and extra expenses can be calculated in the stochastic eqs. [6] to [9] as follows:

Effective Expenses (EE) = 100 * Total Expenses ($/m^3) / Efficiency (%)

$$[6]\qquad \text{EE} = 100\left[\sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij}\right] \Big/ \left(100 - \sum_{k=1}^{r}\sum_{h=1}^{l} W_{kh}P_{kh}\right)(\$/\text{m}^3)$$

$$[7]\qquad \text{Extra Expenses (XE)} = \text{EE} - \text{TEE}\ (\$/\text{m}^3)$$

From eqs. [1] and [6], then,

$$[8]\qquad \text{XE} = \left[100\left[\sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij}\right] \Big/ \left(100 - \sum_{k=1}^{r}\sum_{h=1}^{l} W_{kh}P_{kh}\right)\right] - \sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij}\ (\$/\text{m}^3)$$

Then,

$$[9]\qquad \text{XE} = \left(\left[\sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij}\right]\left[\sum_{k=1}^{r}\sum_{h=1}^{l} W_{kh}P_{kh}\right]\right) \Big/ \left(100 - \left[\sum_{k=1}^{r}\sum_{h=1}^{l} W_{kh}P_{kh}\right]\right)(\$/\text{m}^3)$$

Each delay factor contributed to the total delays with a percent. Current research developed models to measure the effect of each delay factor on extra expenses. In other words, the models consider how much each factor increases the CBP expenses so that remedial actions can be taken. To do so, the relative delay for each factor (R_{kh}) is determined. However, DP is different from R_{kh} in that the first determines the delay percent out of total CBP working time and the second determines its relative percent out of total delay time. The value of R_{kh} can be determined using eq. [10] as follows:

Table 1. Fitted normal probability distributions for probability of occurrence of various delay types (P_{kh}).

	Uncontrolled delays			Controlled delays			
Criteria	No work	Pouring	Weather	Management	Cement	Aggregates	Mechanical
μ	0.1840	0.0540	0.0460	0.4300	0.0940	0.0800	0.1380
σ	0.0631	0.0152	0.0434	0.4422	0.0114	0.0453	0.0390
95% confidence (C)	0.0226	0.0054	0.0155	0.1582	0.0041	0.0162	0.0140
μ + C	0.2066	0.0594	0.0615	0.5882	0.0981	0.0962	0.1520
μ − C	0.1614	0.0486	0.0305	0.2718	0.0899	0.0638	0.1240
KS*	0.2040	0.1462	0.2046	0.2305	0.2371	0.2538	0.2778
Critical value at $\alpha = 0.20$	0.446	0.446	0.446	0.446	0.446	0.446	0.446
Reject H_0?	No	No	No	No	No	No	No
AD†	0.4184	0.3264	0.2988	0.4411	0.2318	0.8174	0.3600
Critical value at $\alpha = 0.20$	1.3749	1.3749	1.3749	1.3749	1.3749	1.3749	1.3749
Reject H_0?	No	No	No	No	No	No	No

Note: Number of observations is 55 data points in each set. H_0, the data follow a normal distribution; H_a, the data do not follow a normal distribution.
*Kolmogorov–Smirnov test statistics.
†Anderson–Darling test statistics.

Table 2. Fitted normal probability distribution and 95% confidence interval for the percent delay duration of various delay types (W_{kh}).

	Uncontrolled delays			Controlled delays			
Criteria	No work	Pouring	Weather	Management	Cement	Aggregates	Mechanical
μ	16.0440	4.9760	3.7100	19.4580	5.5480	3.4020	6.7880
σ	8.2682	0.4064	4.3568	8.5491	1.5991	2.4655	2.7522
95% confidence (C)	2.9587	0.1454	1.5590	3.0592	0.5722	0.8823	0.9848
μ + C	19.0027	5.1214	5.2690	22.5172	6.1202	4.2843	7.7728
μ − C	13.0853	4.8306	2.1510	16.3988	4.9758	2.5197	5.8032
KS*	0.1500	0.1986	0.2661	0.2446	0.1690	0.1584	0.1661
Critical value at $\alpha = 0.20$	0.446	0.446	0.446	0.446	0.446	0.446	0.446
Reject H_0?	No	No	No	No	No	No	No
AD†	0.2019	0.4070	0.4367	0.5478	0.3454	0.2405	0.1864
Critical value at $\alpha = 0.20$	1.3749	1.3749	1.3749	1.3749	1.3749	1.3749	1.3749
Reject H_0?	No	No	No	No	No	No	No

Note: Number of observations is 55 data points in each set. H_0, the data follow a normal distribution; H_a, the data do not follow a normal distribution.
*Kolmogorov–Smirnov test statistics.
†Anderson–Darling test statistics.

$$[10] \quad R_{kh} = 100 W_{kh} P_{kh} \Big/ \left[\sum_{k=1}^{r} \sum_{h=1}^{l} W_{kh} P_{kh} \right] (\%)$$

Therefore, each factor shares in the total expenses with a value (delay factor share (DFS_{kh})) as shown in the following eq. [11]:

$$[11] \quad \text{DFS}_{kh} = R_{kh} \times \text{XE}/100 \ (\$/\text{m}^3)$$

From eqs. [8] and [9], the DFS_{kh} can be determined using eq. [12] as follows:

$$[12] \quad \text{DFS}_{kh} = W_{kh} P_{kh} \left[\sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} \right] \Big/ \left(100 - \left[\sum_{k=1}^{r} \sum_{h=1}^{l} W_{kh} P_{kh} \right] \right) (\$/\text{m}^3)$$

Case study

Five concrete batch plant sites (in the State of Indiana, USA) have been selected to implement the designed models, verify their robustness in assessing delays, and assess their influence on efficiency, cost, and time. Data were collected from each site over a period of 5–6 months. Several techniques have been used to collect data: (1) CBP daily reports; (2) interview with CBP management through site visits and telephone calls; and (3) direct data collection forms that are completed during site visits. Causes of delay were collected from each site and categorized during actual visits. Some plants recorded main causes of delay and their duration in daily reports but other causes were not recorded. In such occasion, the authors identified delay intervals from daily reports and feedback from the CBP management about the causes for these delays. Other factors were identified from daily reports, with the help of CBP management, from the

Fig. 1. Probabilities of various CBP delay types.

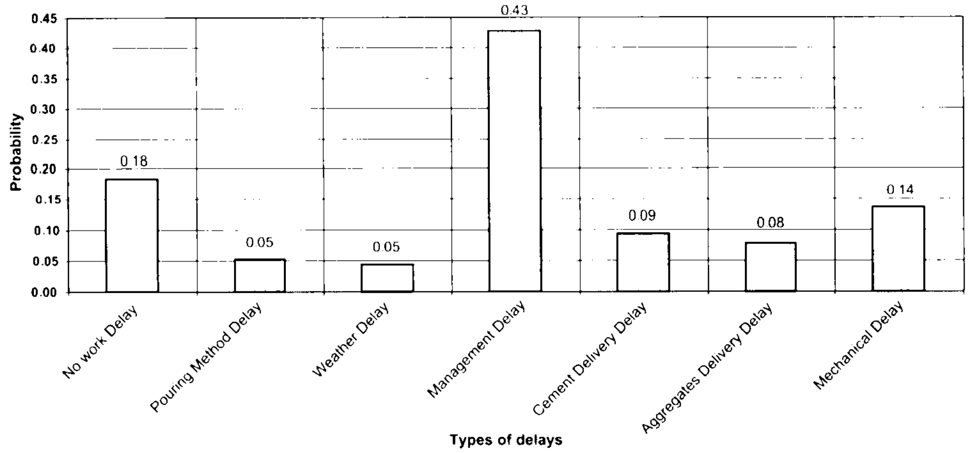
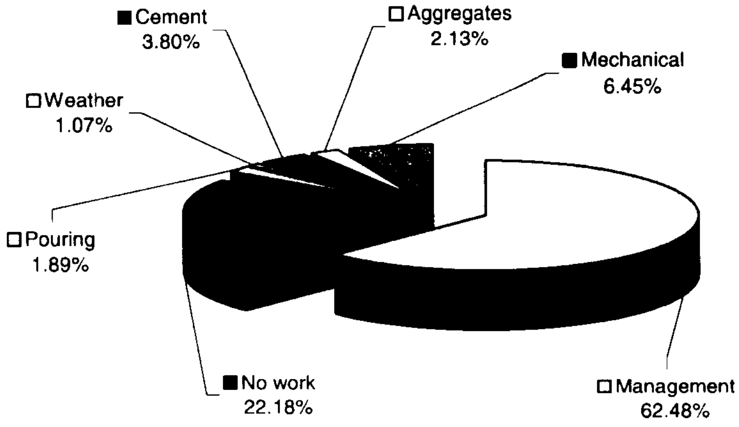


Table 3. Delay types analysis.

		Uncontrolled delays time and percent						Uncontrolled delays time and percent							
		No work delay time		Pouring delay time		Weather delay time		Management delay time		Cement delay time		Aggregates delay time		Mechanical delay time	
Plant No.	Total study time (h)	(h)	W (%)	(h)	W (%)	(h)	W (%)	(h)	W (%)	(h)	W (%)	(h)	W (%)	(h)	W (%)
1	1429	121	8.5	75	5.2	106	7.4	345	24	96	6.7	77	5.4	153	10.7
2	1033	107	10.4	51	4.9	0	0.0	56	5.4	31	3.0	19	1.8	39.5	3.8
3	1582	283	17.9	68	4.3	147	9.3	399	25.2	86	5.4	0	0.0	130	8.2
4	2274	667	29.3	121	5.3	0	0.0	390	17.2	161	7.1	89	3.9	109	4.8
5	2778	394	14.2	141	5.1	51	1.8	705	25.4	153	5.5	163	5.9	178	6.4
Total	9097	1572	**17.3**	456	5.0	304	3.3	1895	21	527	5.8	348	3.8	609.5	6.7
Probability			0.18		0.05		0.05		0.43		0.09		0.08		0.14
Delay%			3.18		0.27		0.15		8.96		0.54		0.31		0.92

*Percent of delay duration (W) for a specific delay type within the total delays.

Fig. 2. Relative percent for delay factors.



average duration for each activity. In other words, loading a 7.6 m^3 (10 cubic yards) truck mixer usually takes approximately 10 min. If it takes, for example, 20 min, the authors recognize the extra time as potential delay. The CBP management was asked for potential causes of these delays to distinguish a delay from a loading time variation. Similar analysis was used to assess types of delay in other activities of CBP operation. Data were processed and analyzed statistically to be ready for the implementation of developed models.

Results analysis

The collected data set is used to calculate the probability of occurrence of each delay type, using eq. [2]. Probability distributions of the probability of occurrence (P_{kh}) are fitted

Table 4. The expected value of delay percent and efficiency at 95% confidence interval for each plant.

	Uncontrolled delays percent and probability (*P*)						Controlled delays percent and probability		
	No work delay		Pouring delay		Weather delay		Management delay		Cement
Plant No.	%	*P*	%	*P*	%	*P*	%	*P*	%
1	8.46	0.12	5.25	0.03	7.42	0.07	24.14	0.45	6.72
2	10.36	0.17	4.94	0.05	0.00	0.01	5.42	0.47	3.00
3	17.88	0.25	4.30	0.07	9.29	0.11	25.21	0.39	5.43
4	29.34	0.13	5.32	0.06	0.00	0.01	17.15	0.46	7.08
5	14.18	0.25	5.07	0.06	1.84	0.03	25.37	0.38	5.51
Average		0.18		0.05		0.05		0.43	

Fig. 3. Total (plant + transporting) expenses for each plant site.

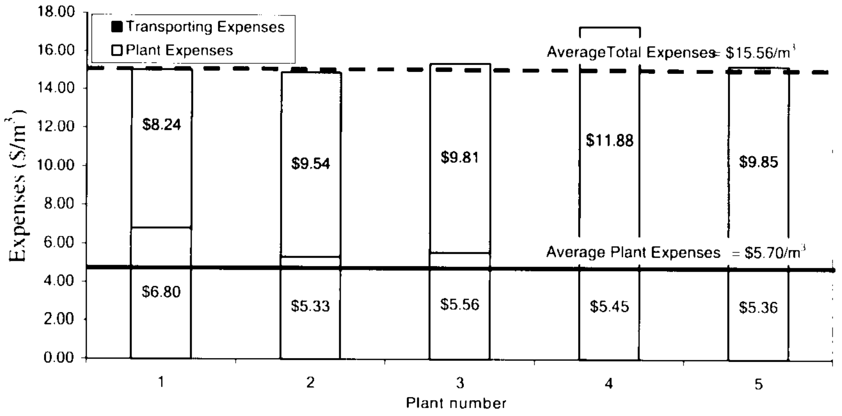
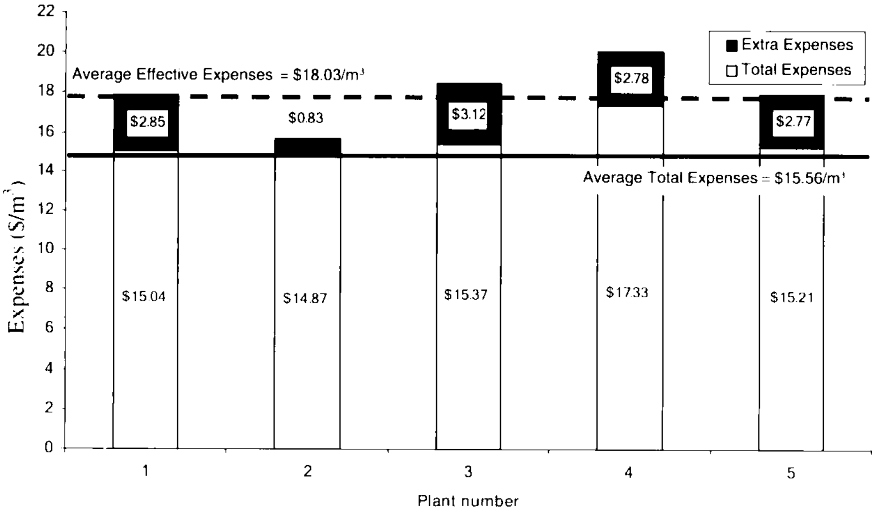


Fig. 4. The expected value of effective and extra expenses for each plant because of inefficient work.



to represent each delay type in the developed models, as shown in Table 1. Two statistical tests are used to select the best probability fit for each delay type: Kolmogorov–Smirnov (KS) and Anderson–Darling (AD). Table 1 shows that normal distribution is the best fit for all delay type probabilities. It also shows the mean (μ) and standard deviation (σ) for each type. The test statistics for KS and AD and the critical values at significance level $\alpha = 0.20$ are shown in Table 1, as well. From KS and AD test statistics, it is concluded that normal probability distribution cannot be rejected as the best fit for the available UD and CD variables using 20% significance level. Similarly, the normal distribution cannot be rejected at 1%, 5%, and 10% significance level. For example, the critical value for "no work" variable at 20% significance level is 0.446 using KS and 1.3749 for AD; however, the test statistics are 0.2040 and 0.4184 for KS and AD, respectively. Because the critical values are higher than test statistics for both methods, a null hypothesis, in which the best probability fit is normal distribution, cannot be rejected. Similarly, the rest of the variables are analyzed; where the majority shows a normal distribution is the best fit. For simplicity and brevity, the current paper considers the expected values and a 95% confidence interval for most of the stochastic variables in analyzing results of

delay	Aggregates delay		Mechanical delay		Plant total delay (%)			Plant efficiency (%)		
P	%	P	%	P	Lower	Ave.	Upper	Lower	Ave.	Upper
0.11	5.39	0.09	10.70	0.20	9.92	15.92	23.13	76.87	84.08	90.08
0.09	1.84	0.00	3.82	0.12	2.55	5.29	9.16	90.84	94.71	97.45
0.08	0.00	0.11	8.22	0.10	10.52	16.88	24.43	75.57	83.12	89.48
0.10	3.91	0.10	4.79	0.15	8.77	13.84	20.08	79.92	86.16	91.23
0.09	5.87	0.10	6.41	0.12	9.19	15.40	22.82	77.18	84.6	90.81
0.09		0.08		0.14	8.19	13.47	19.92	80.08	86.53	91.81

Table 5. The 95% confidence interval (lower, average, and upper limits) for effective and extra expenses.

		Efficiency confidence interval			Effective expenses (EE) confidence interval (US$)			Extra expenses (XE) confidence interval (US$)		
Plant No.	Total expenses (US$)	Lower	Average	Upper	Lower	Average	Upper	Lower	Average	Upper
1	15.04	76.87	84.08	90.08	16.69	17.88	19.56	1.66	2.85	4.52
2	14.87	90.84	94.71	97.45	15.26	15.70	16.37	0.39	0.83	1.50
3	15.37	75.57	83.12	89.48	17.18	18.49	20.34	1.81	3.12	4.97
4	17.33	79.92	86.16	91.23	19.00	20.11	21.69	1.67	2.78	4.36
5	15.21	77.18	84.60	90.81	16.75	17.97	19.70	1.54	2.77	4.50
Average	15.56	80.08	86.53	91.81	16.97	18.03	19.53	1.41	2.47	3.97

Table 6. The 95% confidence interval (lower, average, and upper limits) for uncontrolled relative delay percents and their factors.

	No work (%)			Pouring (%)			Weather (%)			Total UD (%)		
Plant No.	Lower	Ave	Upper	Lower	Ave	Upper	Lower	Ave	Upper	Upper	Ave	Lower
1	5.41	6.38	7.04	1.26	0.99	0.83	3.22	3.26	3.32	9.88	10.63	11.19
2	42.77	33.32	28.02	8.37	4.67	3.08	0.00	0.00	0.00	51.14	37.99	31.09
3	32.27	26.48	23.25	2.55	1.78	1.37	6.94	6.05	5.57	41.76	34.32	30.20
4	32.33	27.55	24.54	3.22	2.31	1.78	0.00	0.00	0.00	35.55	29.86	26.32
5	27.77	23.02	20.47	2.93	1.98	1.50	0.04	0.36	0.68	30.74	25.36	22.65
Average UD% =										**33.81**	**27.63**	**24.29**

Table 7. The 95% confidence interval (lower, average, and upper limits) for controlled relative delay percents and their factors.

	Management (%)			Cement (%)			Aggregates (%)			Mechanical (%)			Total CD (%)		
Plant No.	Lower	Ave	Upper	Lower	Ave	Upper	Lower	Ave	Upper	Lower	Ave	Upper	Lower	Ave	Upper
1	61.98	68.23	71.52	6.56	4.64	3.60	3.35	3.05	2.88	18.22	13.45	10.81	90.12	89.37	88.81
2	28.88	48.21	58.20	8.18	5.11	3.67	0.00	0.00	0.00	11.80	8.68	7.04	48.86	62.01	68.91
3	48.82	58.24	63.44	3.51	2.58	2.07	0.00	0.00	0.00	5.91	4.87	4.29	58.24	65.68	69.80
4	48.52	57.00	62.22	7.12	5.12	3.97	2.90	2.83	2.78	5.91	5.20	4.72	64.45	70.14	73.68
5	53.85	62.62	67.07	4.61	3.22	2.51	4.54	3.81	3.44	6.26	4.99	4.34	69.26	74.64	77.35
Average CD% =													**66.19**	**72.37**	**75.71**

the developed models. Similarly, Table 2 shows the fitted normal probability distributions for the percent of delay duration (W_{kh}) values of each delay type. It further shows the mean (μ), standard deviation (σ), test statistics of KS and AD, and critical values at 20% significance level for various delay types. It also shows the 95% confidence interval for each delay. For example, the percent of delay duration of "no work" factor has a 95% confidence interval limit of 0.1614 (lower limit) and 0.2066 (upper limit). However, its average value is 0.1840, and the normal distribution fit test was successful.

The probability of occurrence for different delay types is shown in Fig. 1. It shows that management delays have the highest probability of occurrence (0.43). Delay due to weather conditions has a very minimal effect on the CBP operation because it has a probability of 0.02. Other delay

Table 8. The 95% confidence interval (lower, average, and upper limits) for delay factor share (DFS) of uncontrolled delays.

Plant	No work ($/m^3)			Pouring ($/m^3)			Weather ($/m^3)			Total UD ($/m^3)		
No.	Lower	Ave	Upper	Lower	Ave	Upper	Lower	Ave	Upper	Lower	Ave	Upper
1	0.09	0.18	0.32	0.02	0.03	0.04	0.05	0.09	0.15	0.16	0.30	0.51
2	0.17	0.28	0.42	0.03	0.04	0.05	0.00	0.00	0.00	0.20	0.32	0.47
3	0.58	0.83	1.16	0.05	0.06	0.07	0.13	0.19	0.28	0.75	1.07	1.50
4	0.54	0.77	1.07	0.05	0.06	0.08	0.00	0.00	0.00	0.59	0.83	1.15
5	0.43	0.64	0.92	0.05	0.05	0.07	0.00	0.01	0.03	0.47	0.70	1.02
Average UD cost =										0.44	0.64	0.93

Table 9. The 95% confidence interval (lower, average, and upper limits) for delay factor share (DFS) of controlled delays.

Plant	Management ($/m^3)			Cement ($/m^3)			Aggregates ($/m^3)			Mechanical ($/m^3)			Total CD ($/m^3)		
No.	Lower	Ave	Upper	Lower	Ave	Upper	Lower	Ave	Upper	Lower	Ave	Upper	Lower	Ave	Upper
1	1.03	1.94	3.24	0.11	0.13	0.16	0.06	0.09	0.13	0.30	0.38	0.49	1.49	2.54	4.02
2	0.11	0.40	0.87	0.03	0.04	0.06	0.00	0.00	0.00	0.05	0.07	0.11	0.19	0.51	1.03
3	0.88	1.82	3.15	0.06	0.08	0.10	0.00	0.00	0.00	0.11	0.15	0.21	1.05	2.05	3.47
4	0.81	1.59	2.71	0.12	0.14	0.17	0.05	0.08	0.12	0.10	0.14	0.21	1.07	1.95	3.21
5	0.83	1.73	3.02	0.07	0.09	0.11	0.07	0.11	0.15	0.10	0.14	0.20	1.07	2.07	3.48
Average CD cost =													**0.97**	**1.83**	**3.04**

types have a moderate probability of occurrence ranging from 0.05 to 0.18.

Delay data from the CBP sites are averaged to calculate the delay percent (eq. [3]) for each type, as shown in Table 3. Results show that management delays have the highest percent (8.96%); however, delay due to no work has the second highest percent (3.18%). Weather delay has the lowest percent (5%). The relative delay percent for each delay type is determined as shown in Fig. 2. It shows that management delays represent 62.54% of the total delays. The controlled delays represent 74.93% and the uncontrolled delays represent 25.07% of the total delays.

Table 4 shows the efficiency calculation based upon the delay percent for each plant, as shown in eq. [5]. The expected value of the efficiency of plant 2 is the highest (94.71%), whereas plant 3 is the lowest (83.12%). The 95% confidence interval limits are lower limit = 76.87 and upper limit = 90.08. However, for plant 2, they are lower limit = 90.84 and upper limit = 97.45. Therefore, with 95% confidence, the efficiency of plant 2 will be between 90.84% and 97.45%. The average efficiency for all plants is 86.53%; however, the 95% average confidence interval limits range from 80.08% to 91.81%. Therefore, on average, 13.47% of the CBP operating time is lost because of delays. The CBP management can raise their plant's efficiency by reducing the delays, whether they are controlled or uncontrolled. In addition, delays raise the total concrete unit expenses, which can be calculated in terms of EE as shown in eq. [6]. Figure 3 shows the total expenses per cubic metre for different plant sites. The total expenses consist of plant and transporting expenses. The average plant expense is \$5.70/m^3; however, the total average is \$15.56/m^3. Figure 4 shows the expected value of effective and extra expenses due to delays for each plant. It shows that plant 2 has the highest expected value of XE (using eq. [9]); however, plant 1 has the highest expected value of EE per cubic metre (using eq. [6]). The average EE is \$18.03/m^3, which is larger than the average total expenses (\$15.56/m^3) by \$2.47/m^3.

From the expected value of the efficiency and its 95% confidence interval limits, the 95% confidence interval limits for effective and extra expenses are determined as shown in Table 5. It shows that the 95% confidence interval limits for plant 1 range from \$16.96/m^3 to \$19.56/m^3 with an expected value of \$17.88/m^3. However, the same limits of extra expenses range from \$1.66/m^3 to \$4.52/m^3 with an expected value of \$2.85/m^3. On average, with 95% confidence, the effective expenses range from \$16.97/m^3 to \$19.53/m^3 with an expected value of \$18.03/m^3. However, the same limits of extra expenses range from \$1.41/m^3 to \$3.97/m^3 with an expected value of \$2.47/m^3.

Tables 6 and 7 resulted from the application of eq. [10] to the various delays in each plant. They show the relative delay percent of each delay factor in each plant. It is noticed that management delay has the highest relative weight in all plants. Delays due to management actions represent almost 50% of the plant delays. This shows how much plant management can do to alleviate delays due to management actions and as a result reduce expenses. Delay because of no work has the second highest relative weight in all plants except for plant 1. These results show that management of these CBPs should increase its marketing efforts or relocate its CBP to increase workload. Delay due to mechanical repair has a considerable relative weight for each plant. Tables 6 and 7 show that the average UD relative weight percentage is 27.63; however, the average CD relative weight percentage is 72.37. The 95% confidence interval for UD and CD range from 24.29% to 33.81% and 66.19% to 75.71%, respectively. It shows the high possibility of improving efficiency and reducing expenses by controlling the CD elements. The CBP management can play a vital role in reducing their CD, which increases CBP efficiency.

Each delay factor share (DFS) can be determined according to eq. [12], as shown in Tables 8 and 9. After calculation of extra expenses (XE) using eq. [9], these XE will be distributed to the delay factors based upon their relative weight percent as shown in eq. [12]. Table 8 shows that the highest DFS in UD factors is no work, which increases the expenses and expected value of \$0.18/m^3 and \$0.28/m^3 for plants 1 and 2, respectively. In addition, the UD increases the expected value of total expenses by \$0.64/m^3. It is noticed that, with 95% confidence, the increase in expenses due to UD factors ranges from \$0.44/m^3 to \$0.93/m^3 with an expected value of \$0.64/m^3. As mentioned earlier in the analysis, management delays have the highest share. It increases the expected value of total expenses by, as shown in Table 9, \$3.12/m^3 and \$2.85/m^3 for plant 3 and 1, respectively. On the other hand, the CD increases the expected value of total expenses by \$2.05/m^3 and \$2.54/m^3 for plants 3 and 1, respectively. On average, the 95% confidence interval limits of increased expenses due to CD range from \$0.94 to \$3.04, with an expected value of \$1.83/m^3.

Based upon the aforementioned results, the authors recommend that the CD, particularly management conditions, should be improved by developing (*i*) control systems for both plant and pouring sites layout, (*ii*) a system to select the appropriate number of trucks required for each project based upon Zayed and Halpin (2001), (*iii*) a regular maintenance system for the plant elements and truck mixers, and (*iv*) a material requirement planning chart for the CBP to reduce delays due to cement and aggregates deliveries. It is also recommended to develop an automated tool that assists in managing the CBP based on the developed models. Furthermore, other types of delays should be considered in future studies to improve the accuracy of these models.

Limitations of current research

Current research provides cost management models that might be applied to any CBP regardless of its location. These models have been applied to a case study of five CBP in the State of Indiana to show their significant benefits to the CBP management. All expenses are restricted to the State of Indiana and the companies that data were collected from. Costs are different from one location to the other, even in the same state, depending on the available market. Therefore, generalizing the cost figures in this research is an impossible process, but any CBP management can use the framework and developed models to evaluate and improve their CBP operation. Current research shows that the developed models and framework can be generalized; however, costs are limited to the case study. In addition, delay percentages will vary with company and location in the same company based on surrounding conditions, such as rural or urban areas, road and traffic conditions, distance, and location. Therefore, delay percentages cannot be generalized.

Conclusions

The CBP operation is affected by many factors, which are identified, categorized, and analyzed in current study. Several cost management models were developed to assess the CBP efficiency and effective expenses. The results show that management conditions (delays because of incorrect number of truck mixers, pouring crew skills, and site conditions) have the highest probability of occurrence, delay percent, and relative delay percent. Results also illustrate that delays due to mechanical problems and to no work have high delay percent. The average efficiency for all plants is 86.53%; however, average total expense is \$15.56/m^3. On average, with 95% confidence, the effective expenses (EE) range from \$16.97/m^3 to \$19.53/m^3 with an expected value of \$18.03/m^3; however, the same limits of extra expenses (XE) range from \$1.41/m^3 to \$3.97/m^3 with an expected value of \$2.47/m^3. It is noticed that, with 95% confidence, the increase in expenses due to UD factors range from \$0.44/m^3 to \$0.93/m^3 with an expected value of \$0.64/m^3. Similarly, the 95% confidence interval limits of increased expenses due to CD range from \$0.94/m^3 to \$3.04/m^3 with an expected value of \$1.83/m^3. The developed models show their significant benefits to the CBP management. These models and framework can be applied to any CBP regardless its location, but the cost figures and delay percentages are limited to the case studies.

Current research is relevant to both industry practitioners (CBP managers) and researchers. It develops models to determine the effect of delays on concrete unit cost. This will identify the source of delays, their relative effect on the concrete unit expense, and determine the plant operation efficiency.

Acknowledgements

The writers wish to express their gratitude and appreciation to the ready mixed concrete companies that generously allowed us to collect data and access their sites. The cooperation and assistance of managers and operators of various plants are also gratefully acknowledged and appreciated.

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