A simulation-based model for evaluating the performance of ready-mixed concrete (RMC) production processes

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Abstract: The development of the infrastructure sector and the rise in the per capita consumption of cement and concrete over the years have triggered the rapid increase in the use of ready-mixed concrete (RMC) in India. The assured quality of concrete, accuracy in the mix proportions, faster construction, less workforce and improved workspace utilization make RMC advantageous over site-mixed concrete. This industry is turning out to be one of the most promising in terms of income and revenue that efforts have to be made to ensure that the RMC production processes are carried out in a timely and cost-effective manner. With the growing concern over the environmental impacts due to construction, its sustainability perspective should also be taken into consideration. This study presents a discrete-event simulation model to evaluate alternate RMC production scenarios and to assess its performance in terms of equipment (batching plant and truck) utilization rate, energy use and carbon emissions. A detailed review on the functioning of the RMC production processes is presented. Finally, this study presents a set of recommendations for improving the performance of the RMC industry.

Keywords: Ready-mixed concrete; discrete-event simulation; production performance; environmental performance.

1. Introduction

The arrival of liberalization principles into the Indian economy paved the way for large-scale investments in the industrial, infrastructural and agricultural sectors of the country. This led to the increased pace in the mechanisation of the construction industry and also to the advent of the usage of RMC in India (Jain, 2002). The use of RMC in the construction industry is significantly advantageous because of many reasons which include good quality concrete, precise mix proportions, faster construction, less number of labourers, reduced congestion at the worksite and improved workspace utilization (Indian Cement Review, 2014).

The size of the RMC industry has grown from USD 2.39 billion in 2009-2010 to USD 6.02 billion in 2014-2015 (Goyal, 2012). As per the earliest efforts to count the number of RMC plants in India, the total number of plants accounted to 27 in the year 2000. This was mainly concentrated to the major
metropolitan cities of India (Jain, 2000). In 2001, this increased to 47 (Jain, 2002) and further increased to 147 by 2005 (Ranganath, 2005). In 2013, the all India commercial count of RMC plants amounted to a total of 857 and the latest statistics as per January 2015 show that the total number of RMC plants is 1135 (Manjunathal et al. 2015).

Most of the plants have been set up in the major cities of India and they account for 30 - 60 % of the total concrete used in these cities. Its use is rapidly increasing in spite of the 12 - 20% higher cost as compared to site-mixed concrete (Alimchandani, 2007). On an average, the total concrete market in India is estimated at about 300 million cubic meters annually. Out of this, the RMC production is about 35 million cubic meters (Goyal, 2012), which is around 12 % of the total concrete production.

Since the country is witnessing a rapid increase in the use of RMC, a comprehensive framework must be set up to address the relevant issues relating to the production and environmental performance of RMC (Misra and Varsney, 2011). This study aims to present an understanding on the functioning of the RMC production processes and to develop a simulation-based model for evaluating alternate RMC production scenarios.

2. Literature review

As a large number of RMC plants are being set up in the country, the industry is turning out to be one of the most promising in terms of revenue and profit. Thus, this also means that the supply, delivery and in-house operations of an RMC plant have to be carried out in a timely and cost-effective manner (Park et al. 2011). To get the maximum cost and time benefit, proper vehicle scheduling and dispatching of the ready-mixed concrete should be maintained. Thus, the project management perspective of RMC has been quite a challenge for its suppliers.

One of the main factors that should be taken into consideration for this aspect is the lifetime restriction of concrete. Concrete is a material which possesses the perishable characteristic that it cannot be stored or produced much in advance. It hardens within a few hours (1 to 1.5 hours) and hence, it has to be delivered from the plant to the site within this time limit (Masten and Sherkow, 2012). This characteristic increases the complexity of the scheduling and dispatching of concrete (Zhang et al. 2011). The production process also depends largely on the distance between the RMC batching plant and the site (Park et al. 2011).

Furthermore, life cycle cost (LCC) has emerged as a significant element in assessing the economic performance of the industry in the long term (Hong et al. 2012). Life cycle cost is the total cost incurred in all the different stages of construction. With this concept, the project management perspective is slowly and steadily merging with the sustainability perspective of construction. There is immense pressure on the world’s environmental performance today that measures have to be taken to conserve the natural resources for tomorrow. It has been shown that humans are exploiting natural resources at a rate of about 20 – 25 % more than the rate at which the earth can replenish them (Gardiner & Theobald, 2014). This applies to the construction sector too as a large amount of raw materials are being used in this industry. Hence, there is an increasing demand in the construction sector, to understand and imbibe the concepts of sustainability in practice.

Many countries have made efforts to reduce the environmental impacts that take place due to construction (Hong et al. 2012). In India, almost 24 % of the total CO₂ emissions is due to the activities occurring in the construction sector (Parikh et al. 2009). It has also been found out that transportation is one of the most significant components which results in the emissions of green-house gases. The
transportation sector contributes to about 23% of the world’s total green-house gas emissions (IPCC, 2008). The transportation of ready-mixed concrete to site represents a major component of energy use and emissions during the on-site construction phase (Palaniappan et al. 2009).

The construction industry consists of complicated, dynamic and interactive processes and like most of the construction processes, the supply and delivery of RMC is stochastic. Thus, the production of RMC cannot be modelled deterministically using average input data. However, it can be efficiently modelled by means of discrete-event simulation (DES). Discrete-event simulation keeps track of the changes of the state of the system occurring at discrete points in time and builds up a logical model of the system to experiment with it on a computer (Lu and Lam, 2009). A lot of work has been done by means of DES to analyse the time, cost and sustainability aspects of earthmoving (Ahn et al. 2009) and road construction operations (Gonzalez and Echaveguren, 2012). In the context of ready-mixed concrete, the use of DES was undertaken in some studies to evaluate the production performance. A brief review of these studies is summarized in Table 1:

<table>
<thead>
<tr>
<th>Problems addressed</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade-off between the transit mixer dispatching interval and queuing time on site by maintaining the number of transit mixers at the desired level to achieve economical RMC supply</td>
<td>Park et al. (2011); Lu and Lam (2009); Zhang et al. (2011); Zayed and Minkarah (2004); Talin (2013)</td>
</tr>
<tr>
<td>Improvement in the concrete delivery performance by adjusting the pour start time at the site</td>
<td>Lu and Lam (2009)</td>
</tr>
<tr>
<td>Maximization of RMC productivity and minimization of cost</td>
<td>Smith (1999); Dunlop and Smith (2002)</td>
</tr>
<tr>
<td>Pump dispatching at the site to reduce the queuing and idle time</td>
<td>Zhang et al. (2011)</td>
</tr>
<tr>
<td>Maintaining the delivery time of RMC to site well within the time limit in order to sustain the best properties of concrete</td>
<td>Park et al. (2011); Zhang et al. (2011)</td>
</tr>
<tr>
<td>Minimization of the resource, market and policy risk associated with RMC supply and delivery</td>
<td>Zhang (2011); Azambuja and Chen (2014)</td>
</tr>
<tr>
<td>Determination of the time, cost and quantity relationship for a required distance from batching plant</td>
<td>Zayed and Halpin (2001); Zayed and Minkarah (2004)</td>
</tr>
<tr>
<td>Web-based quality control of RMC production</td>
<td>Arioz et al. (2006)</td>
</tr>
</tbody>
</table>

Since a lot of studies have been undertaken to take into account the project management perspective, this study aims to calculate the environmental parameters of RMC production processes, which have been relatively unexplored till date. The study aims to determine the truck and batching plant utilization rate along with the energy usage and carbon emissions associated with the RMC processes, while varying parameters such as the total quantity of concrete produced per day, number of trucks, distance travelled per trip and the speed of the truck.

3. Major phases of RMC production

Four case studies were conducted in order to account for the production and environmental performances of RMC processes. This comprised of several field visits to the RMC plants over a period of six months. The RMC plants are located within 100 kilometres of Chennai, the capital city of Tamil Nadu.
A simulation-based model for evaluating the performance of ready-mixed concrete (RMC) production processes in India. A detailed understanding of the RMC processes was developed. The field visits helped in demarcating the RMC processes into five phases and to assess the environmental performance. This was made possible through observations at the plant and interviews with the plant manager and other staff members of each RMC plant. The input for the simulation model was obtained from the analysis of data provided by the RMC suppliers. The RMC production processes are grouped into five major phases from the manufacturing of raw materials to site operations. The disposal of concrete is not considered in the scope of this study. Each phase consumes resources such as water, fuel, electricity, consumables, equipment, vehicles, instruments and human workforce. The details of these five phases are described below (Nellickal et al. 2015):

3.1. Manufacturing of raw materials

The raw materials required for RMC production include cement, sand, coarse aggregates, water, admixtures and flyash. Energy is utilised for the manufacture of cement at the cement plant for the extraction of raw materials, processing, clinker production, grinding and packaging. Coarse aggregates of sizes 20 mm and 12 / 10 mm are usually used for concrete production. Sand is mostly obtained from the riverbeds. Manufactured sand is used in cases when river sand is not available. Flyash is obtained as a by-product from thermal power plants. The admixtures are produced from a wide variety of chemicals. Water is usually obtained from a nearby natural source.

3.2. Transportation of raw materials to batching plant

The raw materials required for ready-mixed concrete production are transported from the supplier location to the batching plant by means of trucks. Cement and flyash are stored in large quantities in silos at the plant while the coarse and fine aggregates are stored in their respective storage yards. The admixtures are transported to the plant in cylindrical barrels which are usually directly connected to the batching plant mixer. Water is brought to the plant in tankers and are filled in the water tanks or is directly obtained from a natural source.

3.3. Operations at the RMC batching plant

The batching plant is fully automated and is run by diesel, electricity or both. The major sources of energy consumption at the plant include the diesel generator, site office operations, loader used for handling aggregates from the storage yard to automated belt conveyor, and the company vehicles. The batching plant is able to produce different grades and types of concrete. The mix proportions are already stored in the automated control systems of the batching plant. The plant uses either a pan mixer or a twin-shaft mixer of specific capacity.

3.4. Delivery of RMC using transit mixer trucks

The batched concrete is then fed into the transit mixer trucks which is transported to the respective customer sites. These are special types of trucks in which the final mixing of the concrete is performed in their rotating drums. For the best properties of concrete to be maintained, the concrete should reach the site within a time limit of 1 to 1.5 hours from the time of batching. This is hindered by heavy traffic on several occasions, especially in the major cities.
3.5. Construction operations at the site

Once the transit mixer reaches the customer site, the concrete is pumped to the required location by means of concrete pump. The placed concrete is further levelled and compacted. The surface is then given the final finish using appropriate tools in order to get an even surface of the concrete placed, prior to its curing.

4. Simulation model

The discrete-event simulation (DES) model takes into consideration the various activities and resources that are part of the RMC production processes. It is developed such that it runs for a period of one day, to deliver concrete from the batching plant to one site. The components of the model and its input and output parameters are shown in Figure 1.

The simulation model was tested for four scenarios by varying the quantity of concrete required per day, distance to site, number of trucks and the speed of the truck. The output parameters are batching plant utilization rate, truck utilization rate, energy use and emissions. Table 2 presents the input data used for simulation. This is based on the information gathered from several field visits. The energy use and emissions are calculated from factors which have been obtained from the field analysis. Energy use is calculated using the factor 6.35 MJ / cum / km one-way distance, whereas emissions is calculated using 0.48 kgCO$_2$ / cum / km one-way distance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No. of samples</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity of concrete transported per day (cum/day)</td>
<td>176</td>
<td>100.7</td>
<td>3</td>
<td>342</td>
</tr>
<tr>
<td>Distance travelled per trip (km/trip)</td>
<td>831</td>
<td>36.2</td>
<td>3</td>
<td>104</td>
</tr>
<tr>
<td>One-way distance travelled per trip per truck (km/trip)</td>
<td>364</td>
<td>18.2</td>
<td>2.7</td>
<td>66.2</td>
</tr>
<tr>
<td>Average number of trips per day per truck (trips/day)</td>
<td>364</td>
<td>2.2</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Fuel mileage for transit mixer (km/litres)</td>
<td>75</td>
<td>2.1</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Waiting time at site for transit mixers (minutes)</td>
<td>268</td>
<td>150.7</td>
<td>0</td>
<td>397</td>
</tr>
</tbody>
</table>

The batching plant component in the model represents the pan mixer in which the various raw materials are mixed to produce the ready-mixed concrete. The capacity of the pan mixer is 1 cum per batch or 45.8 cum per hour. It usually runs for an average of 10 hours per day. Materials represent the storage of the raw materials which needs to be loaded into the pan mixer. The produced concrete is then loaded into the transit mixer trucks which have a maximum capacity of 6 cum. It takes approximately 8 minutes to complete one cycle of mixing the concrete and loading it into one transit mixer. The transportation to the site depends on the speed of truck and the distance of the site from the batching plant. The average speed of the truck is assumed to be 40 kmph over a mean one-way distance of 20 km. The transit mixer waits at the site depending on the availability of the pump and the time required for pumping. Pumping of concrete represents the unloading of concrete at the site by the transit mixer. The time required for pumping is assumed to be 15 minutes. Once the concrete is unloaded, the transit mixer truck returns to the batching plant, where they are cleaned prior to its next trip. The cleaning time is considered as 5 minutes. Based on the data gathered, there are about 8 to 14
transit mixer trucks owned by the supplier company. Their utilization depends on the amount of concrete required to be supplied on that particular day. The average quantity of concrete supplied per day is 100 cum.

5. Results

The results of the four scenarios tested using the discrete-event simulation model are shown in Figure 2.

5.1. Scenario - 1: variation of the concrete quantity produced per day

The quantity of concrete required at the site is varied from 50 to 300 cum. The number of trucks available is maintained at 10 while the one-way distance to the customer site is kept at an average of 20 km. It was observed that both the batching plant utilization rate and the truck utilization rate increases as the quantity of concrete to be produced increases. The batching plant utilization rate varies from 0.474 to 0.844 as the concrete required increases from 50 cum to 300 cum. The truck utilization rate increases from 0.521 to 0.859 for 50 cum to 300 cum of concrete. Similarly, the energy use and emissions increase as the concrete quantity increases. Energy use varies from 12693 MJ to 76519 MJ while the emissions vary from 968 kgCO₂ to 5811 kgCO₂.

5.2. Scenario - 2: variation of distance between the batching plant and site

The distance to the site is varied from 10 to 70 km and the number of trucks is kept constant at 10 in this scenario. The quantity of concrete required is also kept at a constant value of 100 cum. It was observed that as the distance to the site increases, the batching plant utilization rate decreases. This means that the plant has more idle time when the distance to site increases. The rate varies from 0.731 to 0.561 as the distance increases from 10 km to 70 km. However, it was observed that the truck utilization rate increases from 0.53 to 0.772 as the distance is varied from 10 km to 70 km. The energy use and emissions increase as the distance to site increases. Energy use varies from 12693 MJ to 88852 MJ as distance varies from 10 km to 70 km. Similarly, the emissions increase from 968 kgCO₂ to 6779 kgCO₂.

5.3. Scenario - 3: variation of the number of transit mixer trucks

The number of trucks is varied from 8 to 14 for a constant one-way distance of 20 km and a required concrete quantity of 100 cum. The batching plant efficiency decreases from 0.697 to 0.643 as the number of trucks used for concrete delivery increases from 8 to 10, after which it is constant at 0.63 when more number of trucks are used. The model showed that the utilization rate of the truck first increases from 0.708 to 0.716 as the number of trucks increase from 8 to 9 after which it decreases from 0.668 to 0.495 as the number of trucks vary from 10 to 14. Also, this scenario has an energy usage of 25386 MJ and emissions at 1937 kgCO₂. A constant value is observed as the energy use and emissions depend on the distance to site, quantity of concrete required and the number of trips undertaken, regardless of the number or trucks utilised.
Figure 1: Simulation model with input and output parameters.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Output parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Quantity of concrete supplied per day</td>
<td>A. Batching plant utilization rate</td>
</tr>
<tr>
<td>2. Pan mixer running hours</td>
<td>B. Truck utilization rate</td>
</tr>
<tr>
<td>3. Time for mixing and loading of concrete into transit mixers</td>
<td>C. Energy use due to transportation of transit mixer trucks</td>
</tr>
<tr>
<td>4. Number of transit mixer trucks</td>
<td>D. Emissions due to transportation of transit mixer trucks</td>
</tr>
<tr>
<td>5. Capacity of transit mixer trucks</td>
<td></td>
</tr>
</tbody>
</table>

a. Scenario – 1: Number of trucks = 10; One-way distance = 20 km

b. Scenario – 2: Number of trucks = 10; Concrete produced per day= 100 cum
c. Scenario – 3: One-way distance = 20 km; Concrete produced per day = 100 cum

D. Scenario – 4: Number of trucks = 10; Concrete produced per day = 100 cum; One-way distance = 20 km

Figure 2: Results of the simulation model (note: the energy use and emissions are related to the transportation of concrete from the batching plant to site).

5.4. Scenario 4: variation of the speed of transit mixer trucks

The transit mixer delivery speed is varied from 20 km/hr to 80 km/hr. The number of trucks is kept constant at 10 with a concrete quantity to be delivered at 100 cum. The batching plant utilization rate increases as the speed of delivery is increased. The efficiency varies from 0.593 to 0.731 as the speed is varied from 20 km/hr to 80 km/hr. The truck utilization rate decreases from 0.731 to 0.53 as the speed increases from 20 km/hr to 80 km/hr. Moreover, the energy usage was found out to be 25386 MJ and emissions at 1937 kgCO₂. The constant value is because the energy use and emissions are not considered as a function of speed in this scenario.

6. Conclusion

This study evaluated the RMC batching plant utilization rate, transit truck utilization rate, energy use and emissions using a simulation model. The following recommendations are presented to improve the production and the environmental performance of the RMC production processes: a) Proper monitoring of the transportation of the transit mixer trucks such that truck dispatching from the batching plant is in accordance to minimise the idle time at the plant and truck waiting time at the customer site; b) Integrate lean concepts into RMC production processes to eliminate the non-value adding activities and wastage at the plant and site; c) As transportation is one of the major sources of energy use and emissions, the determination of the optimal number of transit mixer trucks for efficient concrete production is considered.
delivery can reduce the total impact on the environment; and d) Use of locally available or recycled raw materials such that the total embodied energy is reduced. This would be useful to improve the decision making processes of the RMC suppliers in terms of project management and sustainability metrics. Further studies can focus on considering the supply of concrete to multiple construction sites per day and the determination of the optimal scenario. Also, the effect of the truck speed on fuel mileage can be studied.

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