REAL-TIME DECISION SUPPORT FOR PLANNING CONCRETE PLANT OPERATION WITH AN INTEGRATED VEHICLE NAVIGATION SYSTEM

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Abstract

Integrating a GPS based vehicle navigation system and the latest optimal algorithms, this research aims to develop a real-time decision support platform for concrete plant to provide the optimal solutions for ready mixed concrete delivery. The platform includes fleet tracking system, simulation and optimization tools, and visual interface which is useful to monitor delivery progress, to obtain crucial historical and real-time data for simulation, and to improve the efficiency of the plant operation. This paper presents configuration of the system and performance evaluation based on operational data.

Keywords Simulation; Optimization; Vehicle Tracking; Construction Planning

1. Introduction

Compared with on-site mixed concrete, ready mixed concrete (RMC) is more consistent in its quality and more environmentally friendly, and requires much less space in a building site. These advantages have accounted for the increasing number of construction projects that employ RMC − most of which are situated in urban areas. According to a study of concreting productivity, metropolitan areas typically draw on RMC as the mainstay construction material (Lu et al. 2003). However, due to the perishable nature of concrete, the batching and delivery operation of RMC is a classical just-in-time production system in construction and hence deserves careful resource and operations planning (Tommelein and Li 1999). Late concrete deliveries will cause interruptions to site activities while early concrete arrivals will hold up truck resources and the prolonged truck waiting time may potentially lead to the hardening of the fresh concrete. In coping with the concrete deliveries, a concrete plant manager confronts the challenge of between maintaining the high service standard (i.e. a continuous concrete supply to clients) while also achieving the efficient use of truck resources (Macomber 2003). Generally, years of concrete plant operations experience, effective communication skills, and proficient truckmixer fleet control skills are the indispensable qualifications of a concrete plant operator.

HKCONSIM (Lu et al. 2003) was originally developed to facilitate the batching and delivery scheduling for the typical one-plant-multi-site RMC problems by applying a simplified discrete-event simulation technique, so as to facilitate the evaluation of both delivery service and resource utilization. In order to pursue the optimum solution based on simulation, HKCONSIM was further combined with genetic algorithms (GA) (Lu and Lam 2005) to optimize the production and delivery scheduling. However, the GA was found too slow to deal with practical scenarios and was soon supplanted by a more powerful optimization algorithm – the Particle Swarm Optimizer (PSO), in that PSO can generate the same optimum result in several minutes in contrast with several hours required by GA (Lu et al. 2006a). To provide the input data for updating the simulation model, a truckmixer tracking system was customized to automatically collect and transfer the tracking data to a control center through wireless communications networks (Lu et al. 2006b). The tracking system has not only automated the data collection process but also enabled the real time concrete delivery monitoring in a digital map. The HKCONSIM as well as the vehicle tracking hardware system forms a robust foundation and provides the prerequisites to the ensuing research of developing a real time version of HKCONSIM, which is presented in this paper.

2. HKCONSIM-Real-time System

The real-time uncertain factors (e.g. traffic jams or unexpected interruptions to truck unloading processes in the building site) affect the efficiency of the RMC delivery, and consequently, may render any well-thought production schedule to quickly become obsolete and irrelevant in operating the actual system. To overcome the limitations of the traditional, “static” planning approach, the newly developed HKCONSIM-Realtime solution is able to (1) monitor the delivery process and gather data from the ongoing activities, (2) convert the raw records into simulation-enabling data, and (3) generate the optimum schedule for the immediate future through simulation. Fig. 1 shows the conceptual framework of HKCONSIM-Realtime. The framework is composed of four modules. They are (1) the actual operations which provide input data to the core planning system of HKCONSIM-Realtime, (2) the tracking hardware system which monitors and collects the operations data of trucks, (3) the simulation modeling engine which turns the operations data into the system outputs for performance evaluation, and (4) the optimization engine which searches for the optimum solution based on simulation models. Note that the four modules in HKCONSIM-Realtime are interdependent and logically connected; the resulting optimized production schedule is implemented to guide the actual operations.

The main challenge in developing HKCONSIM-Realtime lies in how to feed the dynamic-data-driven simulation model with real-time data collected by the vehicle tracking system, and further analyze and evaluate possible scenarios through simulation based on seamless data transformation and application aggregation. As such, the system’s real-time response can be used to update the short-term operations scheduling for the immediate future. As shown in Fig. 1, the tracking data in its raw format flows through the different levels of the application framework, transforming into (1) the noise-filtered data ready for passing to the concrete plant control center over the mobile phone networks, (2) the pre-processed data ready for visualization in a digital map enabling system monitoring, and finally (3) the post-processed data in terms of activity-time distributions enabling simulation modeling. The following sections give more detailed descriptions of the essential components of the HKCONSIM-Realtime system.

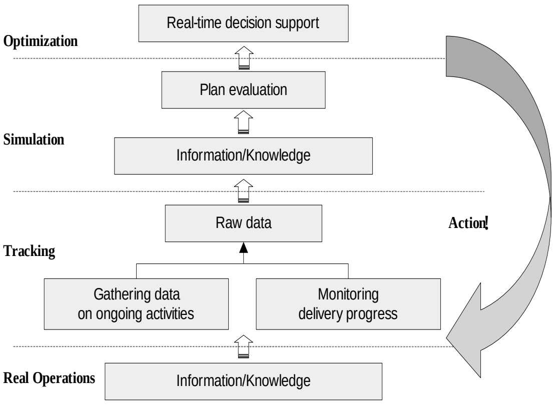


Fig. 1. Framework of the HKCONSIM-Realtime system

3. Optimization Engine

The optimization process of *HKCONSIM* by devising a particle swarm optimization (PSO)-based technique for coping with the optimization of stochastic system simulations. For validating the HKCONSIM simulation platform and further demonstrating simulation-based optimization analysis, one day of complete, detailed operations data (including pour orders, truck-dispatching schedules, concrete delivery slips) were obtained from a concrete plant situated near Tin Wan, Hong Kong Island. On that particular day, the plant utilized two batching bays (mixers), 29 large mixer trucks (7 m^3 volume capacity each) and 15 small ones (5 m^3 volume capacity each) to deliver a total of 952 m^3 concrete to 13 different building sites. Table 1 gives specifics of the pour orders from 13 sites. Note a pour order provides information on (1) the grade and quantity of concrete ordered, (2) the site location, (3) the particular requirement on the mixer truck type (namely, requesting the delivery service by small truck only, or big truck only, or no requirement), (4) the pour start time (i.e. the arrival time of the first mixer truck), and (5) the estimated supply rate (approximated in terms of the interval time between consecutive truck arrivals, or the quantity of concrete delivered per hour m^3/hr).

The plant-to-site travel distance and the placing method employed for each site are linked to the default triangular distributions for travel times and truck-unloading production rates (as shown in Fig. 1, input parameters for triangular distributions are in the order of the optimistic, the pessimistic, and the most likely time estimates in min).

Table 1 Details of Pour Orders processed over one working day

Site ID	Quantity (m^3)	Spec. Truck	First Arrival	Inter-arrival Time (min)	Distance (km)	Placing Method
1	78	Either	8:30	25	3~4	Pump
2	4	Either	10:45	-	3~4	D. Tip
3	5	Either	14:30	-	3~4	D. Tip
4	116	7 m^3	11:00	20	3~4	2 Skips
5	129	7 m^3	9:30	24	3~4	2 Skips
6	54	7 m^3	13:00	25	3~4	2 Skips
7	206	7 m^3	10:30	14	3~4	Pump
8	88	7 m^3	10:45	25	6~10	2 Skips
9	54	Either	12:00	20	6~10	2 Skips
10	88	7 m^3	10:20	30	4~5	2 Skips
11	16	5 m^3	14:00	40	4~5	D. Tip
12	53	Either	13:15	20	4~5	2 Skips
13	61	Either	9:00	30	4~5	2 Skips

The development of a unified quantitative performance measure is critical to evaluating simulated scenarios, and thereby, optimizing the simulated system of *HKCONSIM* with respect to the truck-dispatching schedule and the truckmixer resource provision (Lu et al 2003). A confidence level on the performance measure should also be established due to the probabilistic and stochastic nature of simulation modeling (e.g. the uncertainty in activity duration and the variability in resource allocation in *HKCONSIM*). In the current case study, the performance measure of *"total operations inefficiency" (TOI)* is chosen for evaluating alternatives and determining the optimum state of the system. *TOI* denotes the total unproductive resource time incurred on all the building sites served by the RMC plant in one-day delivery operations by adding up the total queuing time of mixer trucks on sites and the total idle time of site crews. Hence, the less the *TOI* value, the less truck queuing and site idleness experienced within the whole system, and the higher the resource utilization rates of mixer trucks and site crews together with the higher the concrete delivery service level achieved by the RMC plant.

Running the *HKCONSIM* simulation −subject to the actual resource configurations (two batching bays, twenty-nine 7-m^3 trucks and fifteen 5-m^3 trucks) and site order requirements− has resulted in an average of 2720 min *TOI.* Note the *TOI* value from simulation refers to the average of a distribution, resulting from randomly sampling the simulated system for 500 times (i.e. 500 Monte Carlo duplications). The *TOI* distribution's appearance resembles a bell-shaped normal distribution and the 95% confidence interval of the average *TOI* is determined as [2691, 2750]. It should be noted throughout the case study, the evaluation of a simulation scenario by use of *HKCONSIM* is consistently based on the average of *TOI* resulting from 500 Monte Carlo duplications.

Careful analysis of actual operations data and delivery records has determined the actual *TOI* value to be 2670 min, which is a close fit to the 2720 min average *TOI* derived from simulation. The slight difference (50 min) can be attributed to the fact that the actual *TOI* is not a statistical descriptor of the system performance as the simulated *TOI*, but a one-time observation from executing the actual system. The high *TOI* value has also exposed the poor matching performance between supply and demand in the real world (i.e. 2670 min truck queuing plus crew idle time on 13 sites or 205 min per site).

Two site-based performance ratios given by Anson and Wong (1998) imply the average number of trucks seen on a site and the working percentage of the site crew's time respectively, and are instrumental in evaluating system performances and further validating *HKCONSIM* simulation. They are (1) the *truck provision* ratio (*TH/PD%),* defined as the truck provision hours on site over the pour duration, and (2) the *site idleness* ratio (*SI/PD%*), defined as the site idle time over the pour duration. A diagrammatic performance measure can be devised for the one-plant-multisite concrete delivery system by correlating the two ratios in a scatter plot (Fig. 3). The overall trend among all sites can be observed as: with the increase of the *truck provision* ratio, the *site idleness* ratio decreases. The ideal performance is to cluster all sites into the *"cost-efficient"* zone, where the *truck provision* ratio is within 150% and the *site idleness* ratio under 20% (Anson and Wong 1998).

Since the definition of *TOI* also takes into account the truck queuing time on site and the crew idle time, *TOI* can be closely connected with the above diagrammatic measure based on the two ratios. Note the truck queuing is the unproductive portion of truck provision time on site and should be minimized along with the crew idle time in order to enhance the overall system performance. Therefore, if the *TOI* of a *HKCONSIM* simulation can be minimized through optimization, it is expected that the diagrammatic measure will automatically reach its ideal state by clustering all the dots within the “cost-efficient” zone. This connection will be clearly illustrated in the ensuing optimization experiments designed of our case study. To further validate the simulation model, similar to the measure of *TOI*, the diagrammatic measures resulting from actual records and simulation are contrasted in Fig. 2a, b. Fig. 2b gives the correlation pattern of the two performance ratios resulting from the averaged results of 500 Monte Carlo simulation runs, which is observed to well match the actual case as given in Fig. 2a.

Optimization Scenario 1: With the same mixer truck fleet (29 7-m^3 trucks and 15 5-m^3 ones), can the plant operator improve the delivery service by better marshalling the truck dispatching?

In the actual case, the *TOI* stood as high as 2670 min − equivalent to the average of nearly 3.5 hours truck queuing plus site idling as per site. Fig. 2a also reveals in sites no. 11 and 1 the crews were idle over 20% of the pour time (due mainly to late concrete truck arrivals), while sites no. 12 and 7 experienced considerable truck bunching with over 200% *truck provision* ratio recorded. So how can the plant operator provide uninterrupted concrete delivery service to all site customers, while reducing truck bunching on site?

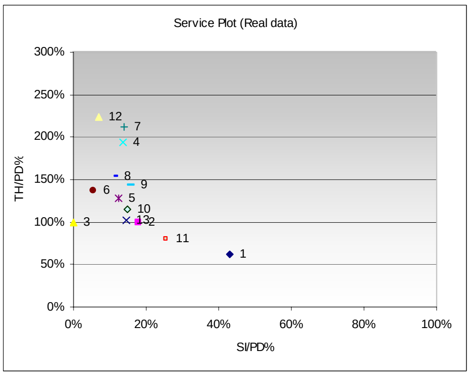


Fig. 2a based on Actual data

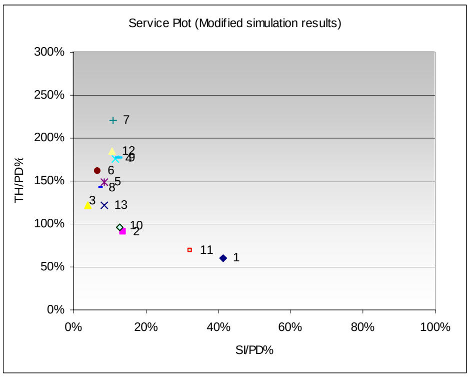


Fig. 2b based on simulation

Fig. 2 Contrasting the diagrammatic measures resulting from actual records and simulation

Based on a valid *HKCONSIM* simulation, optimization analysis can be performed to fine-tune the inter-arrival time for each site within a certain limit of the original estimates (e.g. ±20 min); as a result, an optimum guide can be derived to assist the plant operator in prioritizing site demands and marshalling the truck fleet in a more masterful way, thereby leading to minimization of truck queuing time and crew idle time on all the sites being served. The overall system performance is expected to be sensitive to adjustments on truck inter-arrival times (Smith 1998; Ying et al 2005). In our case study, the optimization brought down the simulated *TOI* from the original 2720 min to 928 min. This is equivalent to a significant decrease on the average of truck queuing plus site idling time per site from nearly 3.5 hours to 1 hr 12 min. Table 2 contrasts the inter-arrival time for each site before and after optimization. Note that for small pours (sites no. 2 and 3) entailing only one truck delivery, optimization of the inter-arrival time is not applicable. On the remaining eight pours the optimization had prolonged the time gap between dispatching consecutive trucks by 1 to 13 min; on three other sites, the time gap had been reduced by 2 to 8 min. Moreover, improvements on system performance are also clearly demonstrated in the scatter plot that correlates the two performance ratios (Fig. 3). In Fig. 3, all sites have been clustered into the *“cost efficient”* zone bounded by the 150% *truck provision* ratio and the 20% *site idleness* ratio. In short, the site demand in terms of the estimate of the inter-arrival time of truck deliveries is found to exert substantial effects upon the overall delivery service level; and optimization of the inter-arrival times for all sites by *HKCONSIM* helps draw up the best concrete production schedule, thereby significantly enhancing the performance of a concrete plant in utilizing the trucks available to meet demands from multiple site clients.

Table 2 Optimization Scenario: inter-arrival time for each site before and after optimization

Site ID	**Original Inter-arrival time**	**Optimum Inter-arrival time**	**Change**
1	25	20	-5
2	-	N/A	N/A
3	-	N/A	N/A
4	20	24	+4
5	24	27	+3
6	25	38	+13
7	14	18	+4
8	25	28	+3
9	20	29	+9
10	30	31	+1
11	40	32	-8
12	20	29	+9
13	30	32	-2

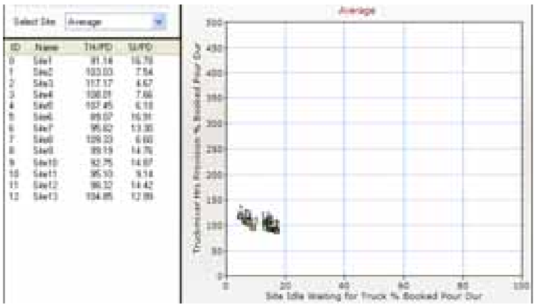
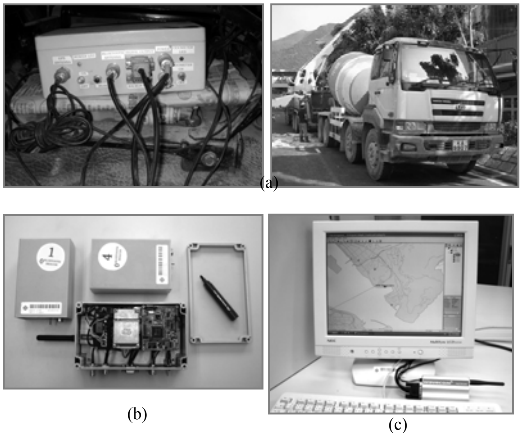


Fig. 3 Site-specific performance ratios and Scatter Plot resulting from HKCONSIM optimization

4. Vehicle Tracking System

The vehicle tracking system consists of a vehicle positioning unit, a communication channel and a control centre (as shown in Fig. 4). The main functions of the system are: a) monitoring the performance of the truckmixers; b) providing actual data for optimization; c) supporting real-time dynamic optimization.

Positioning and communication technologies have evolved over the past decade at a dramatic pace, with their accuracy and robustness continuously increasing while their costs constantly dropping. The technological improvements have made it possible to continuously track construction resources (e.g. construction vehicles). Although the ubiquitous Global Positioning System (GPS) can provide 24-hour and free-of-charge positioning service, the GPS technology suffers signal masking and multipath errors in urban areas and building sites (Lu et al 2004). A recent research has addressed the weaknesses of GPS by integrating GPS with the auxiliary vehicle-navigation technologies of Dead Reckoning and Bluetooth Beacons (Lu et al. 2006b). The “Dead Reckoning” (DR) technology compensates for the masked GPS signals by memorizing the vehicle’s movements (i.e. angle bended & distance traveled), thereby facilitating the determination of the position of the vehicle by basic geometry. Meanwhile, the Bluetooth Beacon (BB) stations are placed at some roadside landmarks −whose exact coordinates are know− so as to correct the position of a vehicle via Bluetooth radio waves when the vehicle passes by these BB stations. Fig. 4 shows the configuration and components of the integrated vehicle tracking system. By relying on such a vehicle tracking system, HKCONSIM-Realtime keeps track of the location and status (i.e. unloading or traveling to the site) of a truckmixer in delivering concrete to a site, and moreover, the tracking data is transmitted back to the control center at the concrete plant via the wireless communications networks in real time.


(a)

(b)

(c)

Fig. 4 Established vehicle tracking system (a) Navigation unit installed under passenger seat of a truckmixer for field trial (b) In-vehicle navigation unit configuration and two Bluetooth beacons (c) Central control computer and interface for real time monitoring

5. Conclusions

Construction simulation models that are driven by input from actual project progress generally serve as a decision support tool for relatively long-term project planning, with the actual site data manually collected and the input models updated on a weekly or monthly basis. In contrast, our research has blended the novel Dynamic-Data-Driven Application Simulation (DDDAS) paradigm into construction operations simulation on a real-time basis by integrating feasible technologies enabling automated data collection and retrieval. Powered by the latest vehicle tracking system, the simplified simulation algorithm, and the efficient evolutionary optimization algorithms, an in-house developed system called HKCONSIM-Realtime provides a decision-support tool for ready mixed concrete business, featuring the functionalities of real time concrete delivery monitoring, optimizing, and re-planning. Enabled by the vehicle tracking system, HKCONSIM-Realtime is kept current of the location and status (i.e. unloading or travel to site) of a truckmixer, and such data is transmitted via wireless communications networks to the control center at the concrete plant, enabling real-time simulation modeling and simulation-based optimization. In summary, the HKCONSIM-Realtime system represents a novel dynamic-data-driven simulation application in construction engineering and management and holds high potential to add cost effectiveness to construction operations and logistics management and customer relationship management in the concrete business.

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