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ANALYTICAL MODELS TOWARDS EXPLAINING THE DIFFICULTY IN EFFICIENTLY MATCHING SITE CONCRETE SUPPLY RESOURCES WITH PLACING CREW NEEDS

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ABSTRACT

Purpose – For parts of the time on a typical construction site concrete pour, the site placing crew is idle waiting for the arrival of the next truckmixer delivery, while, for other periods, truckmixers are idle on site waiting to be unloaded. Ideally, the work of the crew should be continuous, with successive truckmixers arriving on site just as the preceding truckmixer has been emptied, to provide perfect matching of site and concrete plant resources. However, in reality, sample benchmark data representing 118 concrete pours of 69m^3 average volume, illustrates that significant wastage occurs of both crew and truckmixer time. The core purpose of the study was to present and explain the characteristics of the wastage pattern observed and provide further understanding of the effects of the factors affecting the productivity of this everyday routine site concreting system.

Design/methodology/approach – Analytical algebraic models have been developed applicable to both serial and circulating truckmixer dispatch policies. The models connect crew idle time, truckmixer waiting time, truckmixer round trip time, truckmixer unloading time and truckmixer numbers. The truckmixer dispatch interval is another parameter included in the serial dispatch model. The models illustrate that perfect resource matching cannot be expected in general, such is the sensitivity of the system to the values applying to those parameters. The models were directly derived from theoretical truckmixer and crew placing time based flow charts, which graphically depict crew and truckmixer idle times as affected by truckmixer emptying times and other relevant parameters.

Findings – The models successfully represent the magnitudes of the resource wastage seen in real life but fail to mirror the wastage distribution of crew and truckmixer time for the 118 pour benchmark. When augmented to include the simulation of stochastic activity durations, however, the models produce pour combinations of crew and truckmixer wastage which do mirror those of the benchmark.

Originality/value – The basic contribution of the paper consists of the proposed analytical models themselves, and their augmented versions, which describe the site and truckmixer resource wastage characteristics actually observed in practice. A further contribution is the step this makes towards understanding why such an everyday construction process is so apparently wasteful of resources.

INTRODUCTION

This study relates to the efficiency of concrete placing on sites, using ready mixed concrete delivered in batches by truckmixers. Specifically, management intent is the timely arrival of concrete deliveries, such that the concrete placing crew is never idle waiting for concrete to arrive and truckmixers never have to queue on site, waiting to be unloaded. Such, represents a perfect 'matching' performance of truck resources and placing crew resources.

Concreting process

A concrete truckmixer is loaded with concrete at a remote concrete batching plant and driven to the site where its drum is unloaded (emptied) into the formwork by the concreting crew. The unloaded truckmixer returns to the plant to be loaded for its next delivery. Concrete unloading plants include the concrete pump, crane and skip, hoist and barrow, the chute and some others. Both the method used and the nature of the pour affect the unloading duration. Use of a 'concrete pump', in general, leads to faster placing than a 'crane and skip'. A thin vertical wall pour is concreted at a slower rate than a horizontal slab (Anson and Wang, 1994).

A plant manager allocates N trucks to a pour to suit the size of the order. These might be 'serially' dispatched, each truck making one delivery, before, in general, being sent to a different site. 'Circulating' dispatch might alternatively be adopted, whereby a set of N trucks circulates between site and plant, until the pour is completed. In practice, some combination of these two dispatch modes might often apply. It can be noted that circulating dispatch is an example of a 'balance point process' (Halpin and Woodhead, 1976—see Appendix I).

The truckmixer scheduling problem is not easy. Late in the day, deliveries for the following day must be scheduled. Orders are placed by many different sites. Typically, in Hong Kong, one truckmixer makes 4–6 deliveries each day and the number of sites to be covered by the truck fleet available to the plant might be 15–25. Pour sizes vary from 1 delivery at one extreme, to upwards of 25 at the other.

Fig. 1, the motivation behind this study, illustrates the matching of resources achieved for 118 concrete pours placed in 2000/2001 in Hong Kong (Anson et al., 2002; Ying et al., 2005). Each pour is represented on the figure by a single point. The pours received four or more deliveries and averaged 69 m^3 in volume. The largest pour was 208m^3. The horizontal axis, %W, gives the percentage of the overall duration of that pour, spent by the placing crew in waiting for the next delivery of concrete. The vertical axis, %TM, gives the percentage of pour duration spent on site by the truckmixers in queuing and unloading. Ideal resource matching is represented by the point (0,100). Fig. 1 makes clear that very few pours plot in the vicinity of that point.

The lower bound line on Fig. 1 has the equation %W+%TM=100. It is not possible for any point to plot below this line. Any point above this line (practically all points on Fig. 1) means that some truck queuing occurred. The upper line is arbitrarily drawn between points (0, 200) and (50, 50) to include most of the plotted points.

The obvious wedge shaped distribution of the wastage variability, represents an instantly understood 'benchmark' sample of the on-site resource matching performance of the concrete placing industry in Hong Kong at that time. An earlier, 1994, Hong Kong sample of 137 multi-storey building pours, averaging 114 m^3 in volume, demonstrated a very similar pattern (Anson and Wang, 1994, 1998; Wang et al., 2001).

[Insert Fig. 1 here]

The timing details were recorded for every delivery to all 118 pours. For one particular pour of 14 deliveries, Table 1 is a sample of the timing data obtained for all Fig. 1 pours. Truckmixer time spent queuing is the difference between 'arriving on site' and 'starting to unload'. Waiting by the placing crew is the difference between 'finish unloading' of one truckmixer and 'start of unloading' of the next. The variability in journey durations and in unloading durations can also be deduced for each pour. Which dispatch policy applied to each pour, whether a serial, circulating, or some other, is not known.

Purpose of the study

The study arose out of earlier benchmarking studies of concrete pours (Anson et al., 2002) which involved the measurement of placing crew idle times and truckmixer on site idle times, measures reflecting the *standard of co-ordination* achieved between plant and site managements. The main implication of Fig. 1 wastage pattern above is that the overall poor level of co-ordination which seemingly exists, needs to be improved if possible. This study attempted to explain/understand the underlying reasons for the wide degree of variability observed in the degree of co-ordination achieved.

To be successful, any industrial process involving more than one party has to be well co-ordinated. It follows that wastage metrics and an awareness of the scale and causes of wastage, are relevant to all researchers studying the concrete truckmixer scheduling problem and all practitioners involved in site concreting.

Given Fig. 1 wastage benchmark, the authors first developed a basic truckmixer flow analytical model, which relates W, TM wastage to pour characteristic parameters and truckmixer dispatch characteristics.

The study had the three objectives of

(1) developing the basic analytical model and studying its performance predictions;
(2) adding a simulation enhancing capability, augmenting that model, to try to reproduce the wastage distribution pattern of Fig. 1; and
(3) using the enhanced model to attempt to 'explain' the W and TM data of Fig. 1.

The fundamental research question addressed in the study was: *why does that Fig. 1 resource 'wastage distribution' have the shape and scale that it has?* The question is important, because wastage occurs routinely on this everyday construction activity.

The *scale* of the wastages provides hard facts to be consciously improved upon. The *shape* likewise would represent better resource matching overall if the top left hand corner of Fig. 1 wedge was lowered (to remove excessive truckmixer overprovision) and the right hand corner shifted left (to remove excessive truckmixer underprovision). In fact, the upper boundary to the wedge could be lowered as a whole if there were not so many cases of truckmixer waiting for large segments of pours and yet a complete absence of truckmixers for other large segments of the same pour.

Thus, a wedge smaller in area, partly resulting from cleverer scheduling software perhaps and partly from industry concentration on eliminating extreme cases, would represent better utilization overall of industry resources and correspondingly cheaper concrete.

The study is not less relevant because Fig. 1 data relates to the year 2001. The core interest is in how pour parameters, process duration variabilities and disruptions to processes, determine the locations of Fig. 1 plots and their movements to other locations.

PAST RESEARCH RELATED TO THE PRODUCTIVITY OF CONCRETING ON SITE

For about thirty years, the productivity of concrete placing and the related difficult truckmixer scheduling problem have been the subject of research, which can be categorized into productivity benchmarking, simulation based study of the various processes and optimum scheduling techniques. Benchmarking, serves to identify the scale of the problem existing in practice and the influencing factors involved. Simulations enable an understanding of the characteristics of the placing and delivery system as a whole, the productivities to be expected from proposed truckmixer and site schedules and the development of heuristic decision rules for use in practical computer assisted truckmixer scheduling systems. Optimization, for a given set of practical constraints, is concerned with deriving schedules which provide optimum compromises between productivities achieved and, say, the costs of resources utilized.

Although this study belongs to the benchmarking category, the outputs of all three categories of research are relevant to the concreting productivity researcher no matter which group he or she ‘belongs’ to. In the case of this study, the new analytical models are fundamental to the concreting delivery system and must be of interest to researchers in all three categories.

Benchmarking studies

Benchmarking quantifies the real life productivities being achieved for reference purposes by others. Anson and Cooke (1988) benchmarked concreting productivities in a mainly rural area of the UK containing 50 concrete batching plants. Anson et al. (1996) and Anson and Wang (1994, 1998) benchmarked the productivities of different concrete placing methods in Hong Kong for 137 large pours on large buildings. By direct observation, they measured ‘truckmixer-hours provision on site, as a % of overall pour duration’ (%TM) and ‘time spent by the site placing crew, waiting, idle, for a truckmixer to arrive on site, as a % of pour duration’ (%W). They suggested that ‘good matching’ of concrete supply with site placing resources be defined as 100<%TM<150 and 0<%W<10. Anson et al. (2002) similarly benchmarked the performance on 118, rather more representative, Hong Kong pours averaging 69 m^3 (Fig. 1). 83% of those pours failed to achieve the above definition of good matching performance. Lu and Anson (2004) utilized quality control records to benchmark the productivity of the different concrete placing methods. This proved possible in terms of m^3/hour and m^3/truckmixer-hour. Aziz (2017), using 5-year datasets, formulated stepwise regression models to correlate performance ratios with concrete batching plant, travel and site variables.

Simulation studies

Via simulation, Dawood (1995) developed heuristic plant selection and allocation rules to maximize plant utilization at minimum stock costs. Smith (1998, 1999) used discrete event simulation to quantify the overall performance of concrete delivery and site placing, concluding that simulation results can provide reliable performance data for the planning of concrete deliveries to pours on site. Dunlop and Smith (2002) determined optimum truckmixer inter-arrival times on site to maximize concrete pump productivity. Sawhney et al. (1999), using Petri Nets, determined the number of truckmixers to maximize overall productivity for the given concrete volume being delivered that day. Zayad and Halpin (2001) combined discrete event simulation with regression models to formulate probability distributions for such as loading, unloading, hauling and returning durations, leading to optimum resource combinations associated with highest productivities and lowest costs. Wang et al. (2001) simulated concrete deliveries using Excel and @Risk showing, through sensitivity analyses, that productivity is highly sensitive to truckmixer inter-arrival time. Lu et al. (2003) developed the HKCONSIM truckmixer scheduling simulation platform with a user friendly interface for the inputting of concrete orders made by sites. They calculated performance in terms of the productivity metrics suggested by Anson and Wang (1998) above. Feng et al. (2004) developed the RMCDiSO truckmixer schedule simulation platform and Tang et al. (2005) developed the RMCSIM scheduling simulation platform, which modelled deliveries to multiple sites served by multiple plants. They emphasized that overall placing performance is highly related to accurate truckmixer scheduling. Schmidt et al. (2009) proposed a hybrid approach which integrated integer multi-commodity flows with variable neighbourhood optimum search components, producing, they argued, schedules which are more optimal. Misir et al. (2011) proposed a hyper-heuristic approach for simulating concrete deliveries, which outperformed classic heuristic approaches in terms of computational efficiency. Park et al. (2011) developed a system dynamics model of concrete deliveries, which enabled users to assess the impact on performance of the durations of loading, unloading, positioning on site and slump tests. Importantly, they also pointed out that variables representing plant management policies ought to be included if models aspire to represent reality. Examples might be ‘degrees of priority for customers’ and the ‘wish to share deliveries evenly among the truckmixer drivers on duty’.

Optimization studies

Matsatsinis (2004) developed an optimizing model for truckmixer travel routes and timings, for a finite number of truckmixers serving pumped pours on a number of different sites. The timings of the pours were varied to achieve an optimum compromise between customer service and delivery costs. Naso et al. (2004, 2007), for a multi-plant, multi-site scenario used a genetic algorithm to produce schedules minimizing truckmixer costs including those of truckmixer outsourcing and overtime. Wang and Halpin (2004) allocated the available truckmixers to multiple projects using simulation, regression, and mathematical models. The optimum number of truckmixers was allocated to each site such that the overall rate of pouring of concrete was maximized. Feng et al. (2004) formulated concrete delivery schedules using a genetic algorithm which minimized the total idle time of truckmixers on sites. Lu and Lam (2005) used a genetic algorithm to optimize the mix of different capacity truckmixers and their inter-arrival times on site such that delivery performance is maximized. Yan and Lai (2007) and Yan et al. (2008) proposed a mixed integer mathematical model to formulate both concrete production and truckmixer dispatch schedules such that truck operating costs, plant costs, and site and plant overtime costs are minimized. Constraints included plant capacity, site demand, site placement rates, and the time available. Asbach et al. (2009) proved that mixed integer modelling of truckmixer schedules are ‘NP-hard (non-deterministic polynomial-time)’ problems which cannot be easily solved by modern computers. They proposed local search heuristics to help schedule truckmixer routes over a working day. Using bee colony optimization, Srichandum and Rujirayanyong (2010) minimized truckmixer waiting time on site, while maintaining continuous concrete pouring, by routing truckmixers optimally. Hertz et al. (2012) proposed a two-phase solution method for formulating concrete delivery schedules based on linear programming, which selected delivery routes to minimize truckmixer time. Liu et al. (2014) proposed a mixed integer mathematical model and a genetic algorithm to optimize truckmixer and pump schedules which minimized travel and delay costs caused by timing mismatches. Maghrebi et al. (2014) compared the computing efficiencies of ‘column generation’ and ‘robust genetic’ algorithms for deliveries scheduling. In relation to delivery costs, Albayrak and Albayrak (2016) used a mixed integer and a genetic algorithm approach to study the optimum geographical locations of plants in relation to the demands for concrete over a sizeable area.

The above research has led to commercial software scheduling systems which are linked in real time to truckmixer GPS systems. These systems produce start of day truckmixer schedules to meet orders from sites, schedules which can be amended from time to time during the day to take account of actual truckmixer locations. But there is no published data, as far as the authors are concerned, which can be compared with Fig. 1, to check the extent, if any, to which this technology is actually serving to improve resource matching on sites. Such a comparison needs to be made. Indeed, it is entirely possible that these systems are geared primarily towards minimising truckmixer time wastage. Large plants, as in Hong Kong serve many sites on any one day.

Nonetheless, regardless of whatever scheduling system is developed by researchers and the market, and whatever objective function might be under consideration, close matching of site and plant resources must also be achieved on all (or almost all) sites served by a plant on a particular day, *if the system is to be a good one in practice,* in terms of promoting the overall productivity of the process. The highlighting, in this study, of the importance of the coordination criterion and the factors affecting coordination performance are, therefore, of relevance to all in the concreting process scheduling field.

The new analytical models are introduced immediately below followed by their augmented, simulation capable versions, helping to explain the difficulty observed in practice in efficiently matching site concrete supply resources with placing crew needs.

NEW ANALYTICAL MODEL

The model has two components, representing (a) serial, and (b) circulating dispatch policies.

Serial dispatch

Truckmixers are dispatched from plant at intervals of (k×UL), where the parameter UL is the time taken by the site to unload a truckmixer drum. As such, k is the ratio (i.e., any numerical value) of truckmixer dispatch interval to unloading time on site. When k is less than 1, truckmixer dispatch interval is less than truckmixer unloading time. When k is equal to 1, truckmixer dispatch interval is equal to truckmixer unloading time. When k is greater than 1, truckmixer dispatch interval is greater than truckmixer unloading time. The pour requires a total of M deliveries. The first delivery is assumed to arrive on site as required. It is assumed a truckmixer is available for loading at the plant at each scheduled dispatch interval. UL is constant throughout the pour.

The relationships between k, %W, %TM and the number of deliveries, M, are as follows (derivation in Appendix II):

$$\text{If } k<1,\ \%TM=100\times[1+(1-k)\times(M-1)/2)],\ \%W=0. \quad (1)$$

$$\text{If } k=1,\ \%TM=100,\ \%W=0. \quad (2)$$

$$\text{If } k>1,\ \%W=100\times\{(M-1)\times(k-1)/[M+(M-1)\times(k-1)]\},\ \%TM=100-\%W. \quad (3)$$

Circulating dispatch

A set of N truckmixers is assigned to the pour, which circulate between plant and site until the pour is completed. The pour requires an integer multiple of N deliveries. The first N deliveries are dispatched at intervals of UL with the first delivery arranged to reach the site on time. UL, the unloading duration and RT, the time interval ‘leave site to return site’, both remain constant. The batching plant is always available to reload a returning truckmixer.

The steady state relationships between RT, UL, N, %W and %TM are as follows (derivation in Appendix II):

$$\text{If } N<(1+RT/UL),\ \%W=100\times\{1-\{N/[(RT/UL)+1]\}\},\ \%TM=100-\%W. \quad (4)$$

$$\text{If } N=(1+RT/UL),\ \%W=0,\ \%TM=100 \text{ (perfect matching).} \quad (5)$$

$$\text{If } N>(1+RT/UL),\ \%W=0,\ \%TM=100\times(N-RT/UL). \quad (6)$$

By inspecting the equations, it can be seen that the (%W, %TM) resource matching predictions all lie *either* somewhere on the %W=0 line, the left hand boundary of Fig. 1 wedge *or* somewhere on the %W+%TM=100 line, the lower boundary of the wedge [This is a classic balance point process in Halpin and Woodhead (1976) whereby perfect matching of resources is only possible if RT/UL is an integer]. Fig. 2 illustrates the effects on %W and %TM of $0.4<k<1.8$ for N=3, 6, 12 and 18. Fig. 3 illustrates the effects on %W and %TM of $2<N<8$ for RT/UL values between 1 and 9.

[Insert Fig. 2 here]

[Insert Fig. 3 here]

SCOPE OF THE STUDY

The study was divided into the four stages A, B, C and D as summarised in Table 2.

In stage A, new analytical model wastage predictions were assessed and related to those of Fig. 1. UL and k remained constant for all serial dispatch deliveries and RT and UL for all circulating dispatch deliveries.

In stage B, the effects were studied on the stage A results, of significantly changing some RT or UL values, to represent unexpected delays in the arrivals or unloadings of some truckmixers. All RT and UL durations remained deterministic.

In stage C, the true stochastic nature of the variables was recognised. The effects on the A and B results, of allowing RT and UL values to vary within set ranges for all deliveries, were studied. Any RT and UL value had an equal likelihood of being selected for each delivery within the set ranges. The set ranges reflected those ranges typically seen in practice, as informed by the real pour data illustrated by Table 1 above.

Stage D was different in nature. The actual deliveries data was studied for some of Fig. 1 outliers, to check for any further factors which might be contributing to the scale and shape of the Fig. 1 wastage of resources distribution.

[Insert Table 2 Here]

STUDIES MADE

Study A

Serial dispatch

The sensitivity to M is greater when $k<1$ as Fig. 2 makes clear. As M increases, (i.e., pours get larger), the more important it is to ensure k approaches 1 if good resource matching is to occur. If $k>1$, however, the wastage performance worsens with increasing k, but is relatively little affected by the value of M. If unloading on site has a UL of 22 minutes, a dispatch interval of 20 minutes (k=0.91), only two minutes less, results in a %TM already as much as 150% for the case M=12. Since a greater degree of precision than two minutes, in matching truck dispatch to site unloading times is difficult to achieve in practice, even this simple fixed durations model, provides an initial insight into why scatter of some magnitude can occur.

Circulating dispatch

The number of circulating trucks to be allocated, N, is guided by the value RT/UL. If RT equals UL it is obvious that only 2 circulating trucks are needed (i.e., N= 1+RT/UL), regardless of the number of deliveries required. If RT is twice UL, then 3 trucks are sufficient, and so on. But if 1+RT/UL were to equal 4.3, say, not an integer, 4 trucks would be unable to provide an unbroken supply at intervals of UL and 5 trucks would be needed. But, importantly, no more than 5. There would be some inevitable queuing for those 5, but much totally wasteful queuing if 6 trucks were to circulate (It is here again pointed out that this circulating dispatch case is a classic ‘balance point’ construction process, Halpin and Woodhead, 1976. See Appendix I).

After the first set of N circulating trucks has been dispatched, circulating dispatch quickly settles into a self-adjusting steady state whereby the dispatch rate, usefully, conforms with the site's capacity to unload the trucks.

For a given RT/UL value, and a selected N curve, the values of %W and %TM can be read from the left hand vertical axis of Fig. 3. Only those points of discontinuity on the constant N-curves represent cases of perfect matching. The curved lines region of the diagram relates to TM undersupply situations, when N<1+RT/UL .The straight lines region, relates to oversupply conditions when N>1+RT/UL.

When 1+RT/UL is not an integer, the usual case, the next integer 'up' might be chosen for N. The site will never be held up, but trucks will sometimes queue on site. If the integer below is chosen, there will be no truck queuing but the site will sometimes have to wait for deliveries.

Thus, some scatter as seen in Fig. 1 is already inevitable. That scatter, however, as above, extends only along the lower and left hand boundary lines, unlike the spread pattern of Fig. 1.

Matching performance proves to be highly sensitive to the values of RT/UL and N, particularly in truck oversupply situations (N>1+RT/UL). This factor alone can easily produce high values of %TM, of the order of magnitude seen in Fig. 1. So steep, on Fig. 3, are the straight lines of the graph that small reductions in RT/UL result in large increases in truck queuing. This high degree of sensitivity to RT/UL is another fundamental property of the system, particularly applying when there is truck over-supply.

The degree of sensitivity to both parameters, RT/UL and N, is obvious by simple inspection. To illustrate this sensitivity with an example, if RT/UL=3, Fig. 3 indicates that four circulating trucks would provide perfect (0, 100) matching. A choice of 3 circulating trucks would produce %W=25 and %TM=75, demonstrating the sensitivity referred to above and showing the strong placing crew wastage effect of using only one truckmixer too few. 5 circulating trucks, only one too many, produces %W=0, no waiting by the placing crew, but as much as 200 for %TM. These three sets of coordinates are plotted on Fig. 4, to demonstrate this sensitivity graphically. The three plotted points are quite far apart in terms of the scale of Fig. 1.

[Insert Fig. 4 here]

Study B

During study B, the effects of unplanned delays were explored, such as might be caused by placing problems on site, traffic jams, truck breakdowns, temporary lack of trucks at the plant because of service to other pours, or other, including the temporary non-availability of a mixing/loading bay.

Serial dispatch mode

A 12 delivery pour was simulated with the dispatch interval and UL both equal to 20 minutes, to give perfect matching. UL, for load 5 only, was then increased to 40 minutes, a 20 minute slowdown in unloading. This alone increased %TM from 100 to 154, with %W=0. The start of delivery number 4 was then delayed by 15 minutes, having returned UL5 to its initial setting of 20. This irregularity produced %W=5.9 and %TM =141, a point, notably, no longer on a boundary line.

Circulating dispatch mode

Site problems were simulated by increasing UL for chosen deliveries and truck delays, of whatever type, by increases in RT. As far as site production is concerned and Fig. 1 pattern, it is only the effective RT that matters, i.e., the RT value as seen from the site. The specific component of RT causing the delay is not relevant at this level of modelling detail.

4 sets of ‘delay’ experiments, 1 to 4, were made for pours of 12 deliveries (Table 3). As with study A, all RT and UL values were fixed for any simulation run. Those RT and UL values, increased to simulate delays to one or more of the 12 deliveries, were also fixed at those increased values.

The four experiments were based on the following four sets of UL, RT and N:

i. RT=40, N=3, UL=25;
ii. RT=40, N=3, UL=20;
iii. RT=40, N=3, UL=12;
iv. RT=40, N=4, UL=12.

The first three sets have values for RT/UL of 1.6, 2.0 and 3.33 respectively and are served by 3 circulating truckmixers. Sets three and four have the same RT/UL value of 3.33 and are served by 3 and 4 truckmixers respectively.

Each of the four experiments consisted of the five simulation runs A, B, C, D and E immediately below:

(A) The steady state solution given by the newly proposed deterministic model, above (Inputs to A consisted of the four sets of RT, N, UL values immediately above).

(B) As A, but the first set of N deliveries was dispatched at 5-minute intervals, an assumed time for loading and washing each truck. A plant manager, as a common practice and if available, might send out the first set of truckmixers more quickly than necessary, to insure against possible traffic delay.

(C) As B, but a delay of 40 minutes was applied to site unloading of the 6th delivery, i.e., to UL6.

(D) As B, but a 40 minute delay was imposed upon the 6th delivery, i.e., to RT6.

(E) As B, but a ‘very bad’ day was simulated by imposing delays of 40 minutes on two site unloading operations (UL6, UL8) as well as two delays of 40 minutes in delivering concrete to site (RT6, RT8).

Figs. 5 and 6 and Table 3 display the %W and %TM matching performance results as ‘heavy dots’ and demonstrate (1) that scatter away from the boundary lines, as seen in Fig. 1, is reproduced when significant delays occur and (2) that the extent of the scatter is on the same scale as that of Fig. 1 and of the same ‘shape’, in conforming quite well with the wedge and spreading out to fill that wedge in the manner of the real pours. Only point E perhaps, were more often outside the wedge than inside, suggesting that the ‘bad day’, to the extent simulated, does not occur too often in practice.

Fig. 5 compares the effects of a differing RT/UL for a fixed N=3. Fig. 6 compares the effects of a differing N for a fixed RT/UL=3.33. Table 3, additionally, gives the time required in minutes to complete unloading the 12 deliveries in each case.

[Insert Fig. 5 here]

[Insert Fig. 6 here]

[Insert Table 3 here]

N.B., the triangles also plotted on Figs. 5 and 6 relate to study C and are explained below.

The main conclusion is that the form, scale and spread of the scatter produced by these simulations replicate those seen in Fig. 1 including the large departures from the boundary lines.

Study C

For the first time, the effect of the stochastic nature of RT and UL was explored.

Two sets of experiments are reported.

Experiment 1

A pour of 12 deliveries served by 4 circulating trucks was simulated with N=4, RT/UL=3, RT=90 and UL=30. Since N=1+RT/UL and the four trucks were first sent off at 30 minutes intervals (equal to UL), perfect matching is the result, as represented on Fig. 7 by the plot at (0,100) for %W and %TM.

12 simulations were then run in 3 groups of four with N=4 in all twelve cases.

- Runs 1–4: RT fixed at 90 minutes. UL averaged 30, respectively within the ranges 28–32, 26–34, 24–36 and 20–40.
- Runs 5–8: UL fixed at 30 minutes. RT averaged 90, within the ranges 85–95, 80–100, 70–110, and 65–115.
- Runs 9–12: Both UL and RT were varied within set ranges. For run 9, the ranges for UL and RT were 28–32 and 85–95 minutes respectively. The range pairings for runs 10 to 12 were (26–34, 80–100), (24–36, 70–110) and (20–40, 65–115).

For all 12 cases each run was performed 5 times. The %W and %TM values plotted on Fig. 7 represent the averages of 5 individual simulations.

[Insert Fig. 7 here]

The effects on matching performance are noticeable but not large. The largest effects, for the 50 minutes RT range and the 20 minutes range for UL (typical of real life ranges), were to increase %W by only 7% and %TM by 25% (But notably always an increase). On this evidence, UL and RT variability is enough to explain only part of the displacement of plots away from the boundary lines of Fig. 1.

Experiment 2

For the cases of Fig. 5 and 6, values for RT and UL, no longer fixed, were sampled from the ranges below, except for those large imposed delays, which were left fixed. The results of these simulations are shown as triangles on Figs. 5 and 6. Each plotted point represents the average of 5 simulations.

The ranges applying to RT and UL were based on a random selection of 15 of the pours given in Fig. 1 data set. Thus, for a mean RT of 40 minutes, a range of 28–52 was set. For UL cases 25, 20 and 12, the ranges were set at 22–28, 14–26 and 9–15 respectively. Simulated RT and UL durations were sampled from within those ranges.

The results show that the stochastic effects on waiting and queuing are relatively small. The larger effects on %W and %TM are produced by delays, as in study B. The pours represented by points C and D, for instance, suffered one sudden UL delay of 40 minutes in the case of C and one sudden RT delay of 40 minutes in the case of D. These delays had the effect of considerably moving the plotted locations, C and D from position B and in different directions. The additional movements, to the triangle plots, due to typical variabilities in RT and UL are smaller, but usually worsened the resource matching performance as in Fig. 7. Interestingly, however, such worsening was not always the case as can be seen by inspection. This needs to be explored in future work.

The serial dispatch case in study B above, where UL and the dispatch intervals were both 20 minutes, was further examined. Each UL value was allowed to randomly vary between 14 and 26 minutes and the dispatch intervals between 18 minutes and 22 minutes. The mean of 5 simulation runs averaged %W=1.9 and %TM =141, no longer perfect matching of %W=0 and %TM=100.

Study D

Some real pour outlier cases from the dataset were studied, to check if additional factors underlying Fig. 1 distribution pattern might also be relevant.

Four high %TM outlier pours

Pours 23 and 94 received 11 and 12 deliveries respectively. These pours were heavily oversupplied with trucks yielding %TMs of 267 and 242 respectively. The flows of pours 23 and 94 are shown in Fig. 8 and Fig. 9.

[Insert Fig. 8 here]

[Insert Fig. 9 here]

The solid bars represent unloading; the dots, when trucks leave the plant; the short vertical line represents arrival on site and the plus sign represents arrival back at the plant and available for reloading.

In the case of pour 23, except for unloadings 1 and 6, UL values lay between 10 and 19 minutes and averaged 14. Since trucks on average were dispatched at 15 minute intervals, there ought not to have been too much queuing. But UL1 took 30 minutes and UL6 took 47 minutes, two rogue unloadings, the latter particularly lengthy, considerably extending TM queuing.

Pour 94 was quite different, in that there were no such rogue delays. The 12 deliveries, however, were dispatched at 13 minute intervals on average, much shorter than the unloading times which averaged 18 minutes, within the range 14 to 23 minutes. The over-fast dispatch rate meant that each successive truckmixer queued for slightly longer than the one ahead. The final truck queued for 50 minutes. With k averaging 0.72, and M=12, serial dispatch theory predicts %TM=254, close to the actual value of 242.

Two large pours, 40 and 21 were next studied. 22 and 21 deliveries were made to each site, but with %TM values of 205 and 209 respectively (Fig. 1). Two trucks, on average, would have been seen on site throughout the whole pour time of 8–9 hours; one being unloaded and one queuing. In both cases, it happened that almost every truck arrived much too early, each queuing for nearly half an hour on average. Such large pours would normally have been carefully planned. The only reasonable explanation, it is speculated, is that the concrete suppliers were especially keen to insure that this large pour was not delayed. As above, Park et al (2011) stated that variables to represent ‘management behaviour’ are necessary components of an optimizing model in the ready mixed concrete supply business.

Outlier pour with high %W

Pour 75, that pour registering the highest %W among all 118 pours, was a 17 trip pour and no small pour therefore. The performance at %W=49 and %TM=55 (Fig. 1) was decidedly poor and yet the site was only 6 km from the plant. The concrete was placed by pump which emptied the truckmixers in 13 minutes on average, but the truckmixers were dispatched at 29 minute intervals on average, with inevitable waiting by the site but virtually no truckmixer queuing. This outlier possibly reflects the reality that a plant serves many sites in parallel and there was too much competition for truckmixers on that particular day. Many pours with high values of %W, not just this outlier, can probably be partly explained by this factor. For pour 75, the average value for k was 2.2. For M=17, serial dispatch theory predicts %W=53, %TM=47, close to the actual values.

Discussion of Study D

It is broadly apparent that good matching is promoted if both unloading times and truck dispatch intervals remain relatively constant and roughly equal. Pour 94, had reasonably constant dispatch intervals and unloading times but there was much truck queuing because the dispatch interval was consistently shorter than the unloading time. The reverse happened with pour 75 with excessive waiting by the site. Pour 23 failed because there were two uncharacteristically lengthy unloadings among the 11 deliveries. Only 2 out of 11, but that was enough to spoil the whole pour. The large pours 21 and 40, however, were perfect in that dispatch intervals and unloading times met the required criteria. The result should have been near perfect but, oddly, all deliveries were sent much too early and each truck queued for 20–30 minutes. Minimizing truck queuing, had clearly not been the principal aim of the concrete plant manager. Pour 118, by contrast, with %W=4.5 and %TM=104, was a good result approaching the perfect matching condition. Like pours 21 and 40, dispatch intervals and unloading times were the same and more or less constant. Unlike pours 21 and 40, however, the first delivery arrived just in time for unloading and not 20 minutes too early.

It seems that Fig. 1 also embodies the consequences of plant management policies, in that, on some pours, customer satisfaction is probably the priority. When truckmixers queue excessively on site, it might be because they were deliberately dispatched early, as a hedge against contingencies.

Another system factor, very likely to affect the dispatch timings, is that several sites are being served in parallel and an outgoing dispatch might be delayed because the whole fleet is ‘off plant’ at the scheduled dispatch time in question. Single plant multi-site simulation experiments, not undertaken in this study, are needed to assess the significance of this factor.

CONDENSATION OF STUDY FINDINGS

Fig. 1 resource matching performance can be seen as the consequence of an unconscious, accepted industry cost compromise between the need to maximize the productivity of placing crews and the need to maximize the usage of delivery truckmixers. Guaranteed perfect site service would require concrete suppliers to possess very large fleets of truckmixers, under-utilised for most of the time, necessarily reflected in higher unit concrete prices.

For circulating dispatch, if RT, UL remain the same for every delivery, for a given N, productivity performance is predicted by the new model of Fig. 3. This model predicts (%W, %TM) performance plots that can only lie somewhere on the left hand boundary or somewhere on the lower boundary of Fig. 1 wedge. To plot at the bottom left hand corner, the only place representing maximum possible productivity, RT/UL must be an integer and N must be the number 1+RT/UL. For serial dispatch, only for dispatch intervals k×UL, where k=1, is such perfect matching possible. Otherwise, for constant journey times, the performance plots similarly lie only on the wedge boundary lines. In reality, dispatch to a pour might not always follow either of those models and is sometimes a compromise between them.

The sensitivity of the system to the correct choice of N and the correct prediction of RT/UL in advance is clearly illustrated by Fig. 3 from simple inspection. Small differences can cause performance plots to move considerable distances along the boundary lines. Similarly, Fig. 2, for serial dispatch, illustrates the degree of sensitivity to changes in k, and to M also in cases of k<1.

To mirror the movements of plots into the body of Fig. 1 wedge, it is only necessary that the unloading of one truckmixer is significantly longer than scheduled or if only one RT value is significantly greater than the others. In other words, only one rogue delivery or one rogue unloading, is enough to generate the spread across the wedge actually seen in reality. If there are several major delays to a pour, rather than just one, the simulated plot is likely to lie outside the bounds of the wedge, suggesting that in real life such circumstances are infrequent.

If every RT and every UL is treated as the stochastic variable it actually is, using the quite wide RT and UL duration ranges seen in practice, further movements of the performance plots are noticeable but not large. Thus, stochastic effects do affect productivity, of course, but not by as much as might be assumed.

Thus, the wide degree of scatter of Fig. 1, scatter away from the boundary lines, is more influenced by disruptions to the flow of truckmixers, whether site generated or otherwise, than by the quite considerable variabilities which routinely apply to the unloading and delivery activities. Site generated delays move plotted points 'upwards'; truckmixer/plant generated delays move points to the 'right'.

A further factor affecting Fig. 1 industry performance pattern is plant management policy. On examining the actual delays and flow patterns of some real pours, it seems that truck dispatch decisions might not always be aimed at minimizing truck productivity, but rather to give priority to a particular customer. This would be a perfectly rational strategy, in the case, for example, of a big pour being undertaken by a client with likely future orders to place.

An important factor affecting the ability to dispatch trucks on schedule, is the fact that a plant usually serves several sites at any one time. All truckmixers may be 'absent from plant', with no truckmixers available at scheduled times of dispatch to specific pours. Single plant multi-site simulation experiments are needed, as future work, to assess the effects of this factor on Fig. 1 distribution.

Two special features of circulating despatch policy should be highlighted, as above in study A. Firstly, plant dispatchers can be directly guided by the pour RT/UL estimate to avoid choosing values for N which will be particularly wasteful. Secondly, circulating dispatch settles into an efficient steady state, whereby the dispatch rate at the plant automatically conforms with site capacity to unload the truckmixers.

Finally, as an observation, Fig. 3 can be seen as a diagram which *augments* balance point theory in relation to a set of circulating concrete delivery trucks, a companion diagram to the classic text of Halpin and Woodhead (1976). It augments, because it also provides information on the wastage of server time (the truckmixers in this application), and not only the wastage of production resources (the placing crew).

CONCLUSIONS

With reference to the 'purpose of the study' above and the benchmark of real life resource wastage depicted by Fig. 1:

(a) The basic analytical models developed, predict the over-provision of truckmixer time (%TM) and wastage of placing crew time (%W) for a given pour for both serial and circulating truckmixer dispatch policies. The models are based on constant values throughout the pour of the parameters M, k, and UL for serial dispatch and the parameters N, RT and UL for circulating dispatch. The range of the magnitudes of the predicted %W and %TM output pairs is similar to that of Fig. 1 but not the distribution of those pairs over the %W, %TM space. The models, as expressed by Figs. 2 and 3, illustrate the high degree of sensitivity of %W and %TM to changes in k, M for serial dispatch and N, RT, UL for circulating dispatch, respectively. This sensitivity is an important system factor underlying variability of wastage time in practice. The model for circulating dispatch enables the choice of the most economic value for N.

(b) Model augmentation, providing a single plant, single site, delivery simulation capability proved able to mirror the distribution of the plotted points of Fig. 1 as well as their magnitudes. The augmented model, therefore, successfully enabled the study of how changes in pour input parameters, would move a (W, TM) coordinate pair from one part of Fig. 1 wedge to another part, a powerful tool for detailed study of system behaviour.

(c) An outline understanding has been gained of why the wastages of time is of the magnitude and form of Fig. 1 that it is, for this everyday relatively simple construction process. Fundamentally, the right number of truckmixers must be deployed to a pour, dispatch intervals at the plant must closely conform to unloading durations on site, and lengthy interruptions (one is enough) to the flow of work must be avoided if %W and %TM values are to be kept within reasonable limits. The system is sensitive, as above, to using the wrong N and M, and to changes in RT, UL and k. The stochastic nature of all operations, adds to the problem, but this factor is not the major generator of resource wastage. As for those many points on Fig. 1, where W<10% and TM<150%, say, the likelihood is that stochastic effects and the inherent sensitivity of the system are sufficient explanation for the variability within that group of outcomes. This is a hypothesis to be explored in future work.

(d) Major moves of the plotted points may also be due to deliberate management policies. A particular client, no doubt for good business reasons, seems sometimes to be ‘guaranteed’ an uninterrupted concrete supply. Truckmixer time may be sacrificed with earlier than necessary deliveries as a hedge against contingencies.

(e) It is suggested that the circulating dispatch analytical model derived during the study represents a contribution to balance point theory. It may not have been pointed out in the literature that this form of concrete supply to sites is a balance point process, but, more importantly, the model, illustrated by Fig. 3, augments the classic balance point analysis by providing server productivity predictions in addition to the traditional producer productivity predictions.

(f) For a specific pour, the proposed analytical models can be used to determine the optimal number of truckmixers and their dispatch timings, which will result in minimum wastage of resources, for a given dispatch policy and estimated average RT and UL times throughout the day. An RT estimate might combine local knowledge, local traffic prediction and Google map, for example, and a UL estimate might be based on site advice. Further work needs to derive analytical models, if possible, giving overall resource wastage for a plant serving multiple sites.

In summary, the overall conclusions on the contribution of the study to society and practice and research are as follows.

1. Resource matching co-ordination performance is highlighted as an important criterion attaching to productivity performance. This is relevant to all researchers in the field. Whatever criteria are otherwise under consideration, when a process involves more than one party, good productivity is not likely to be achieved if coordination is not also good.
2. The new analytical models provide insights into properties of the concreting system itself. The sensitivity to values of the basic pour parameters becomes obvious, thereby partly explaining the spread observed in coordination performance in practice. For any particular pour, the policy of circulating dispatch is picked out as automatically leading to a good fit between plant dispatch rates and the ability of the site to unload truckmixers, i.e., better co-ordination.

3. The detailed simulations studies give rise to the firm hypotheses, alongside the system sensitivities above, that (i) very poor wastage performance on a site is mainly due to a serious delay (one is enough) to a truckmixer delivery or a site problem delay, (ii) the wish to favour a particular customer contributes to some extent, and (iii) normal stochastic effects do affect wastage, of course, but to a lesser extent.

NOTATION

Variable	Definition
W	Placing crew wasted time, idle. Defined as the sum of the intervals between finish unloading each truckmixer delivery and start of unloading of the next.
%W	W expressed as a percentage of pour duration.
TM	Total truckmixer time spent under site control, both in waiting to be unloaded and in being unloaded.
%TM	TM expressed as a percentage of pour duration.
k	The ratio, truckmixer serial plant *dispatch interval*, to *unloading duration* on site.
RT	Truckmixer round trip time, defined as leave site to return back to site via reloading at the plant and assuming no waiting to be reloaded .
UL	Truckmixer drum unloading (emptying) duration on site.
M	Number of truckmixer deliveries required to complete the pour, in the case of serial dispatch.
N	The number of truckmixers in the set circulating between plant and site, in the case of a circulating dispatch policy.
Q	Total time spent on site by all truckmixers in waiting to be unloaded.
P	Pour duration, defined as the period between start of unloading of the first delivery and the finish of unloading of the final delivery.

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APPENDIX I: A CIRCULATING SET OF TRUCKMIXER DELIVERIES—A BALANCE POINT PROCESS

The circulating truckmixer dispatch case is a classic 'balance point' construction flow process, Halpin and Woodhead (1976), and Halpin and Riggs (1992), though not cited by them as such. Halpin and Woodhead discuss a continuous flow pusher-scraper soil removal process which depends on a fleet of circulating scrapers (servers) to remove the soil on a continuing basis, and others.

Balance point processes can *never* achieve 100% productivity for all resources involved unless the production rate of the principal activity is exactly an integer multiple of the production rate of each server unit. Bernold and AbouRizk (2010) cite the case of a concrete batching plant order for aggregate delivered by a series of quarry based trucks. The case of concrete deliveries to site, is almost the reverse of that. The 'production unit' is the concrete placing crew and the 'server unit' is the plant based truckmixer.

In general, a balance point problem is characterized by a loss of productivity for one or other of the production/server plant resources involved, because the *integer condition rarely exactly applies.*

In the example in the text, at the point where this Appendix is referenced, 1+RT/UL=4.3, and there is either a loss of productivity in the placing of concrete, if 4 truckmixers circulate, or else a loss of truckmixer productivity if 5 truckmixers circulate. 100% productivity for both placing crew and trucks requires RT/UL to be an integer and the number of circulating trucks to be 1+RT/UL. If 6 truckmixers were chosen to circulate, however, there would be a great deal of unnecessary wasteful queuing. If 3, there would be much waiting by the placing crew. Thus, even though the integer condition is rarely satisfied, the application of balance point theory is extremely useful in guarding against poor choices. In this case, either 4 or 5 truckmixers may be chosen but definitely not 3 or 6.

APPENDIX II: DERIVATION OF RELATIONSHIP FORMULAE

Serial dispatch relationships between %W, %TM and M deliveries and inter-dispatch time interval

Let UL be site unloading time and inter-dispatch time interval be (k×UL).

Case of k<1

The first truck is timed to arrive on time, with no queuing. The second arrives (1-k)×UL before the end of the first unloading and queues for that time. The third truck arrives (1-k)×2UL before the end of the second delivery and queues for that time. The M^{th} truck queues for (1-k)(M-1)×UL. Total queue time, Q, therefore is: (1-k)×UL multiplied by the sum of the terms in the arithmetic progression: 0, 1, 2, 3,…,(M-1), i.e., by M(M-1)/2. The site never has to wait for concrete and %W=0, therefore, and pour duration, P, is M×UL. %TM is given by 100×(Q+P)/P, or 100×(1+Q/P), i.e., %TM=100×[1+(1-k)(M-1)/2].

Case of k>1

The first truck arrives on site on time, with no queuing. The second arrives (k-1)×UL after completion of the first unloading, i.e., the time the placing gang has to wait. The third arrives (k-1)×UL after completion of the second unloading and the M^{th} truck arrives (k-1)×UL after completion of the $(M-1)^{th}$ unloading. Total site waiting time, W, is therefore (M-1)(k-1)×UL. The overall pour time, P, is M×UL+W, therefore %W=100×(W/P), i.e., 100×(M-1)(k-1)/[M+(M-1)(k-1)]. Trucks are on site for the period M×UL, or P-W, so %TM is 100×[(P-W)/P], or 100×(1-W/P), i.e., %TM=100-%W.

Circulating dispatch steady state relationships between %W, %TM, N trucks in the circulating group and RT/UL

RT is the fixed round trip time for all trips, leave site to return to site, assuming no queuing at the plant waiting to be loaded. UL is the fixed unloading time on site for all unloadings. The total number of deliveries is an integer multiple of N. The N deliveries of the first batch are dispatched at intervals of UL to achieve perfect matching for those N deliveries (i.e., serial dispatch for the first set of N).

Cases when N<1+RT/UL (i.e., RT>(N-1)UL)

For subsequent sets of N deliveries, if RT>(N-1)×UL, only the first of the set, the $(N+1)^{th}$, will arrive later than the N^{th} unloading, by an amount RT-(N-1)UL. The $(N+2)^{th}$ delivery, in contrast, will arrive exactly as the $(N+1)^{th}$ delivery finishes unloading as will all subsequent deliveries until the $2N^{th}$, the last of the second set of deliveries. Exactly the same pattern exists for the third set and for all subsequent sets of N deliveries. To get steady state %W and %TM for all sets of N deliveries, we only need to obtain those results for one set of deliveries. In this case, every truck in each set of N deliveries, except for the first in the set, will arrive in time to be unloaded straight away. The delay, or site wait, due to the late arrival of the $(N+1)^{th}$ delivery, the first in the set, is RT-(N-1)UL and the total pour duration for the second set of deliveries is N×UL plus that single delay. Thus %W=100×[RT-(N-1)UL]/[N×UL+(RT-(N-1)UL)], which simplifies to %W=100×[1-N/(RT/UL+1)]. There is no truck queuing and as for serial batching, above, %TM =100-%W.

Cases when N>1+RT/UL (i.e., RT<(N-1)UL)

In this case, apart from the first set of N deliveries, every individual truck, no matter how many sets of N deliveries are made, will queue for a period (N-1)×UL–RT. Thus, %W, the measure of site waiting for concrete, is zero. Steady state %TM is queuing time plus unloading time as a percentage of unloading time or %TM=[(N-1)×UL-RT+UL]/UL, which simplifies to %TM=N-RT/UL.

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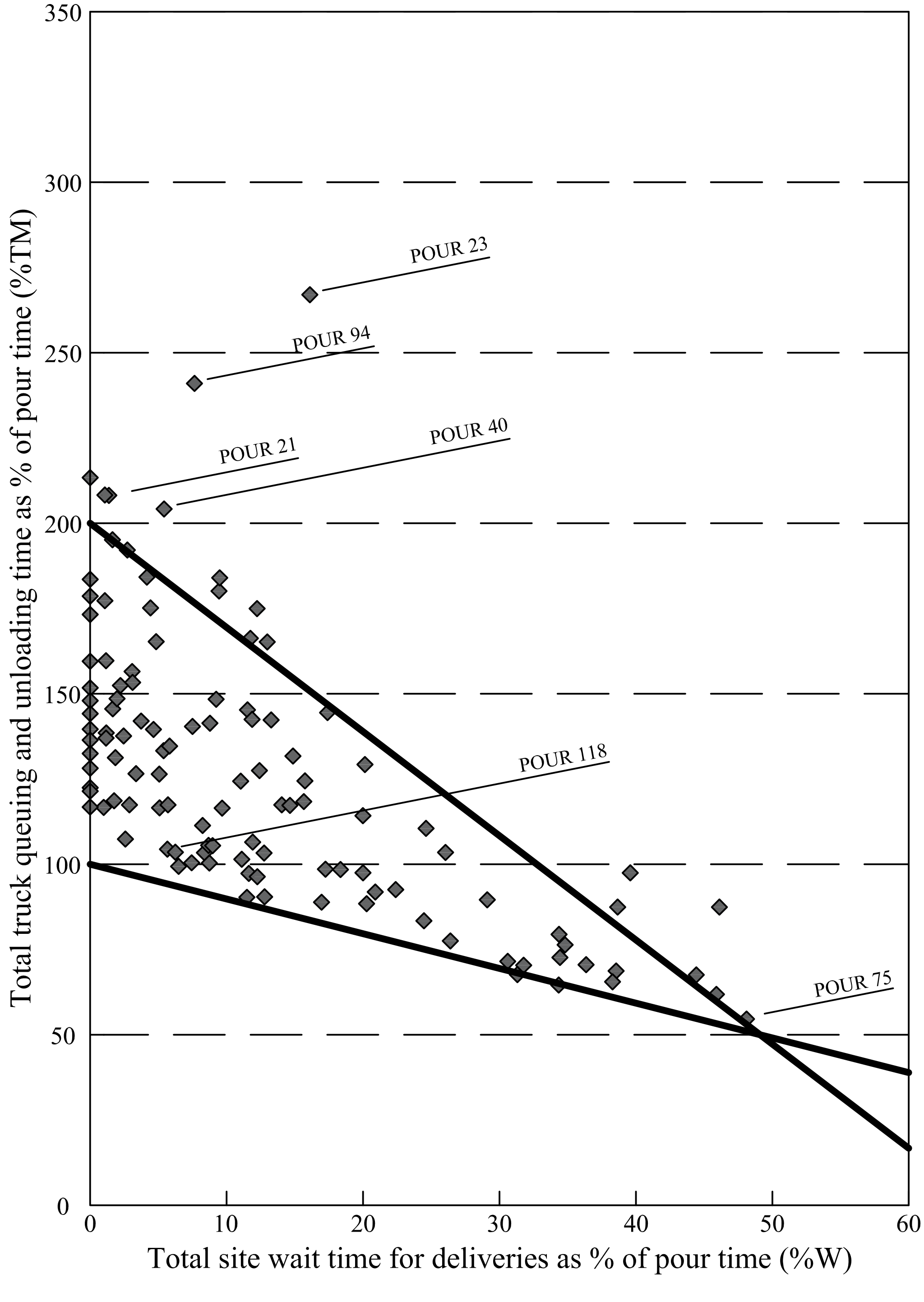
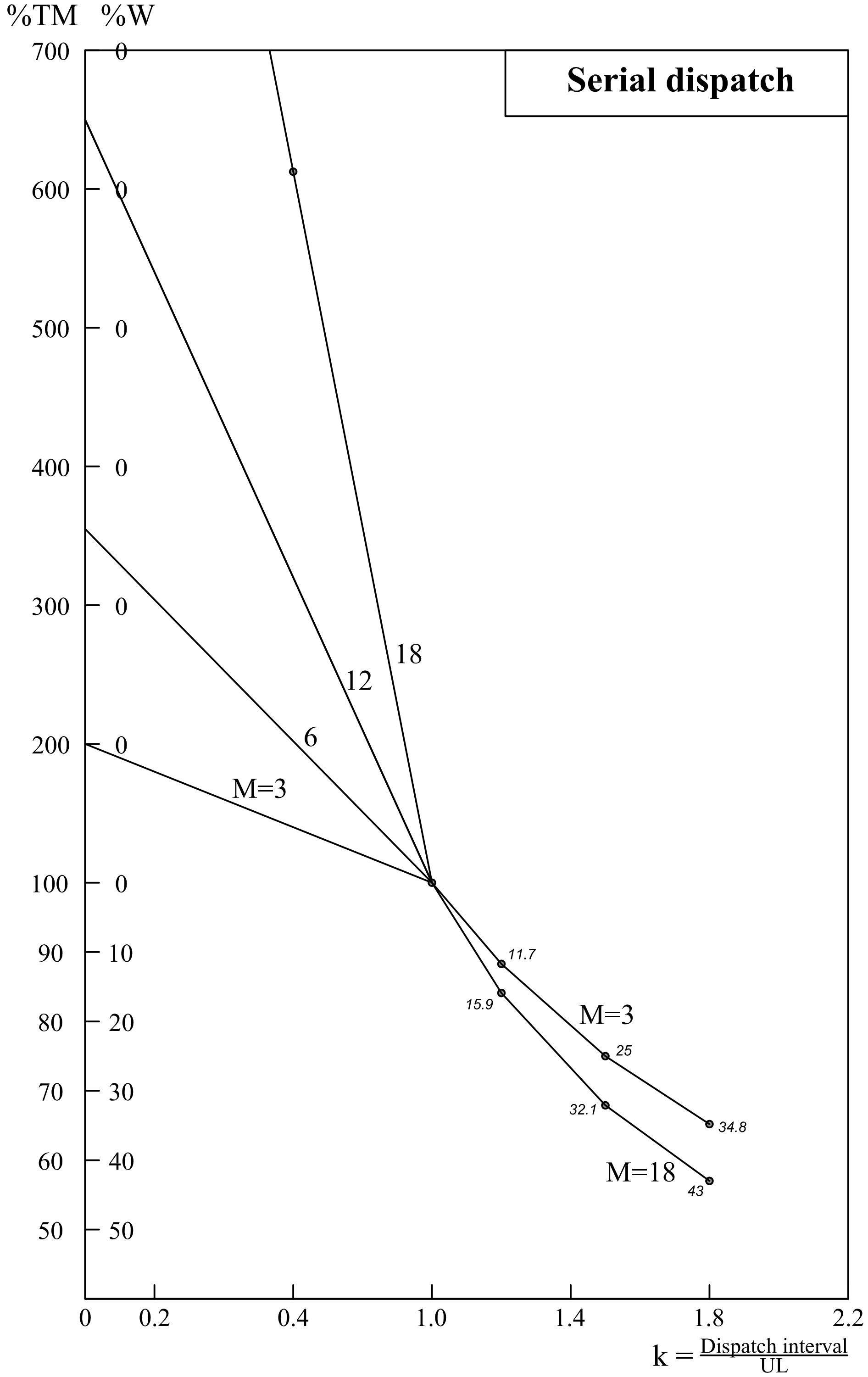
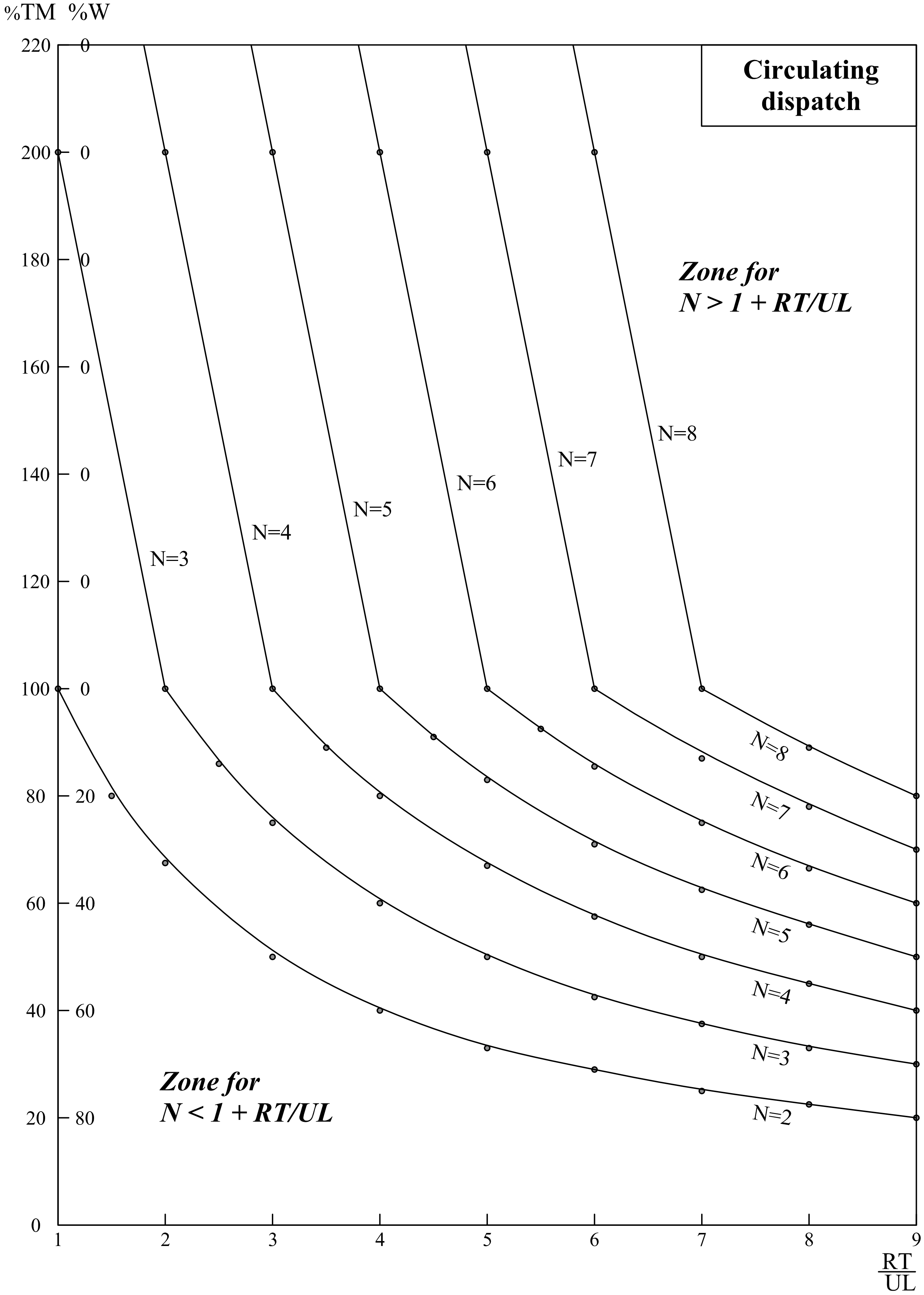


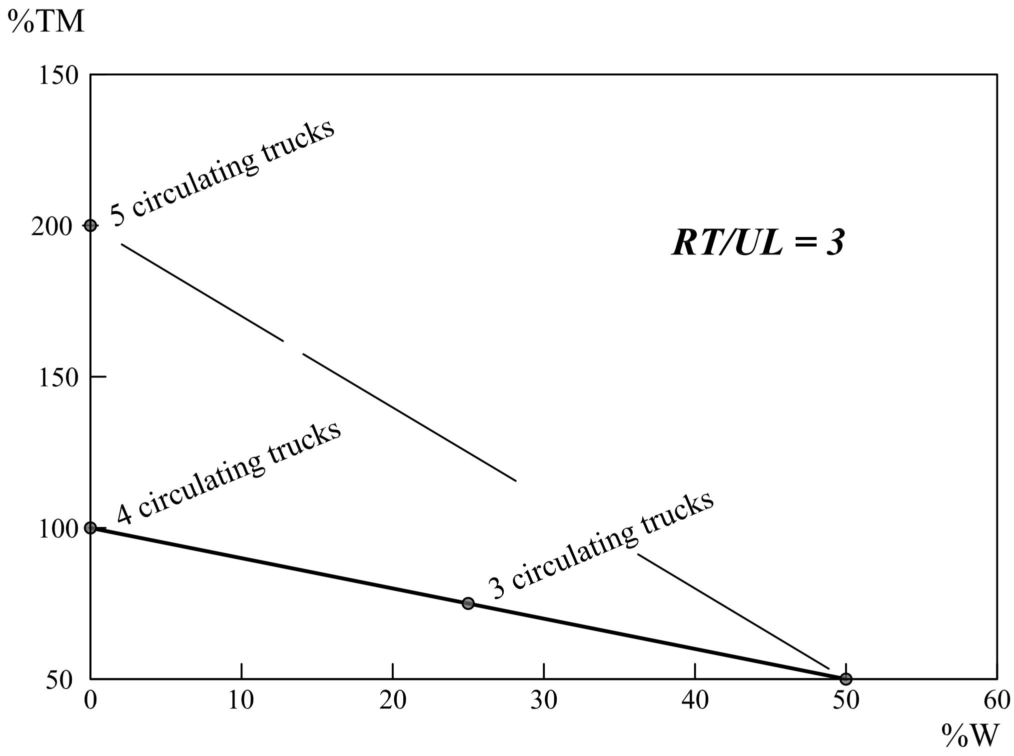
350
300
250
200
150
100
50
0
POUR 23
POUR 94
POUR 21
POUR 40
POUR 118
POUR 75
0
10
20
30
40
50
60
Total truck queuing and unloading time as % of pour time (%TM)
Total site wait time for deliveries as % of pour time (%W)

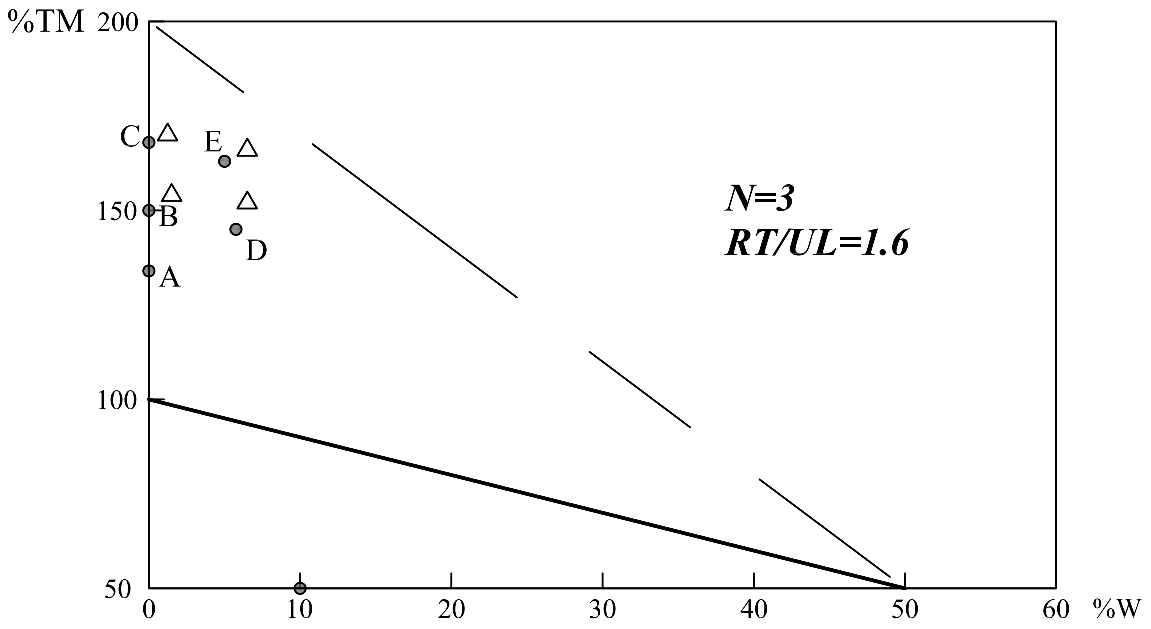


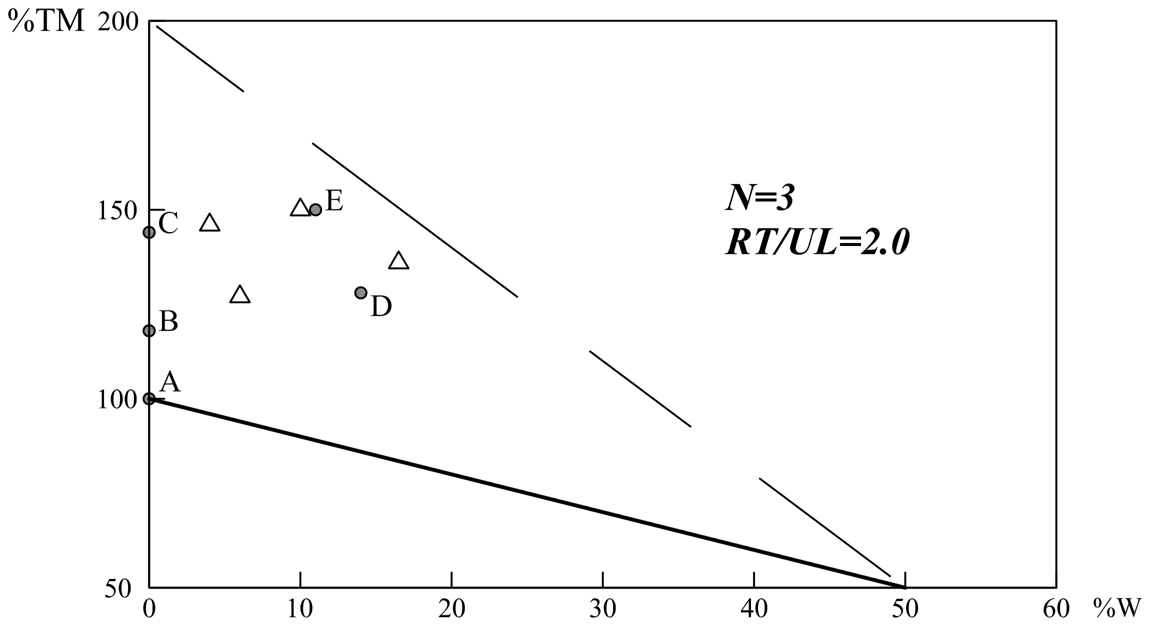
%TM
%W
Serial dispatch
700
600
500
400
300
200
100
90
80
70
60
50
0
10
20
30
40
50
M=3
6
12
18
11.7
15.9
25
32.1
34.8
43
M=3
M=18
0
0.2
0.4
1.0
1.4
1.8
2.2
k = Dispatch interval / UL

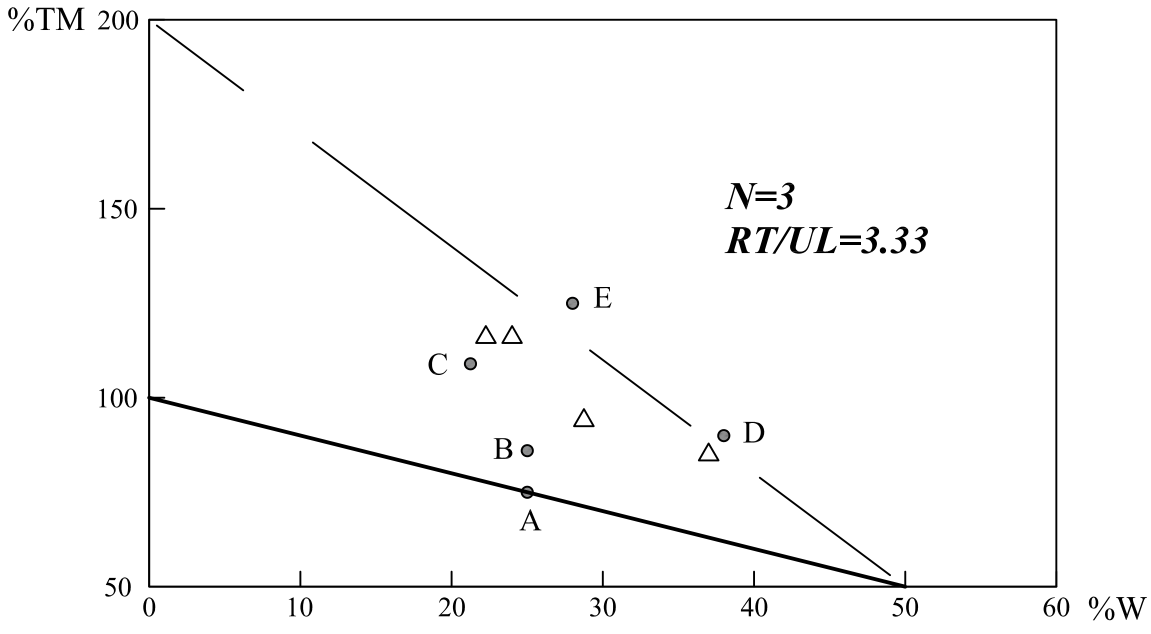


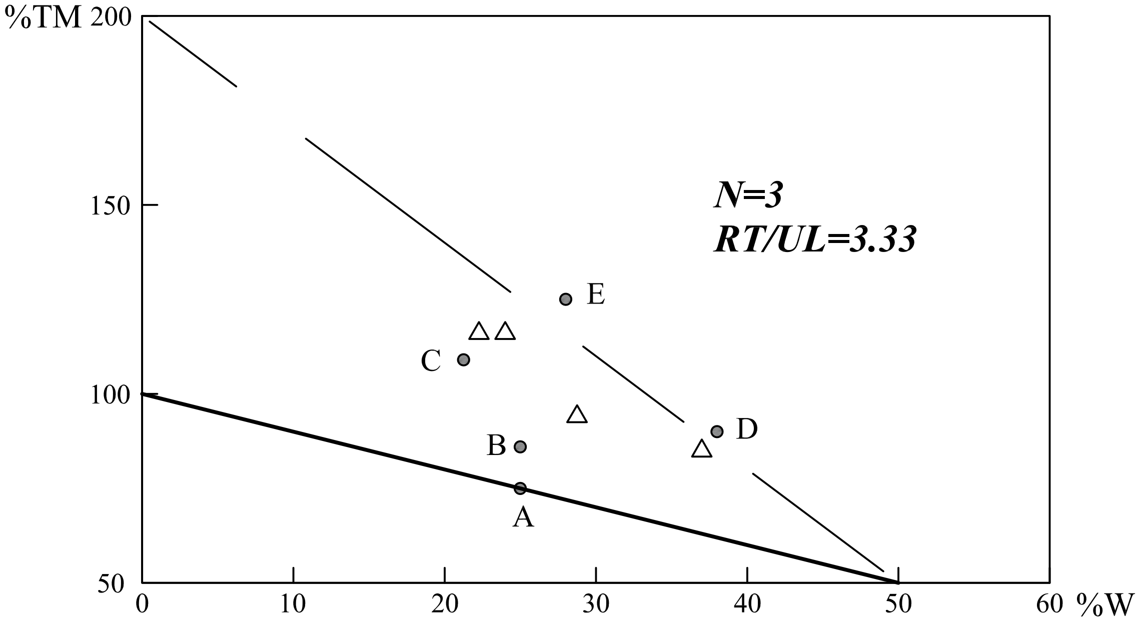
%TM %W
Circulating dispatch
Zone for N > 1 + RT/UL
Zone for N < 1 + RT/UL
N=3
N=4
N=5
N=6
N=7
N=8
N=2
220 0
200 0
180 0
160 0
140 0
120 0
100 0
80 20
60 40
40 60
20 80
0
1 2 3 4 5 6 7 8 9
RT/UL


%TM
150
200
150
100
50
5 circulating trucks
4 circulating trucks
3 circulating trucks
RT/UL = 3
0
10
20
30
40
50
60
%W

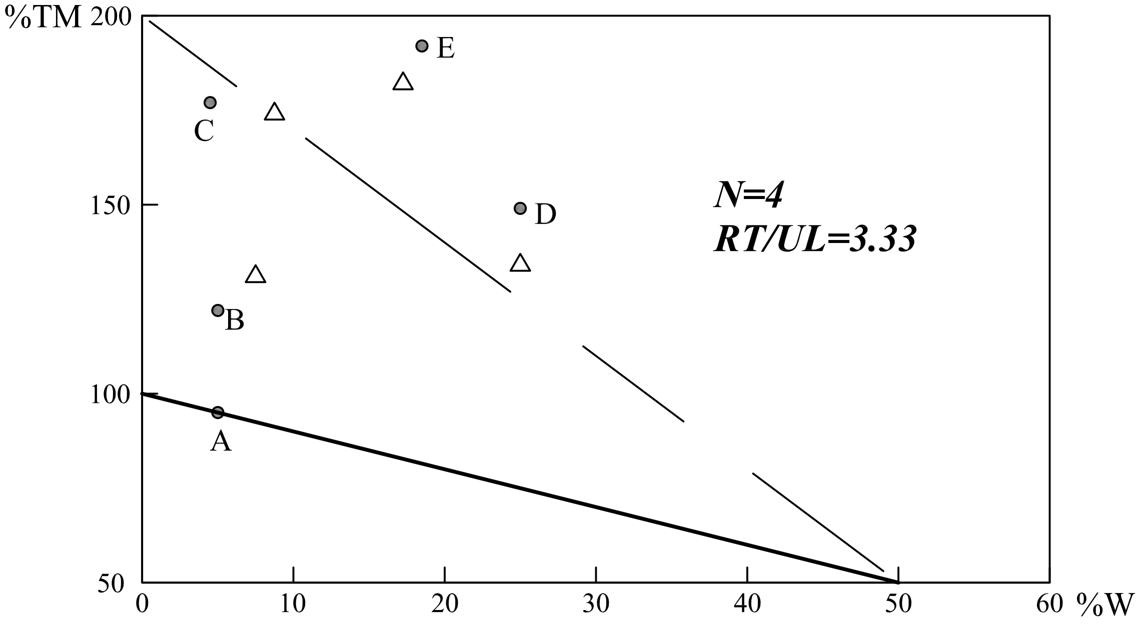

%TM
200
150
100
50
0
10
20
30
40
50
60
%W
A
B
C
D
E
N=3
RT/UL=1.6


%TM
200
150
100
50
0
10
20
30
40
50
60
%W
A
B
C
D
E
N=3
RT/UL=2.0

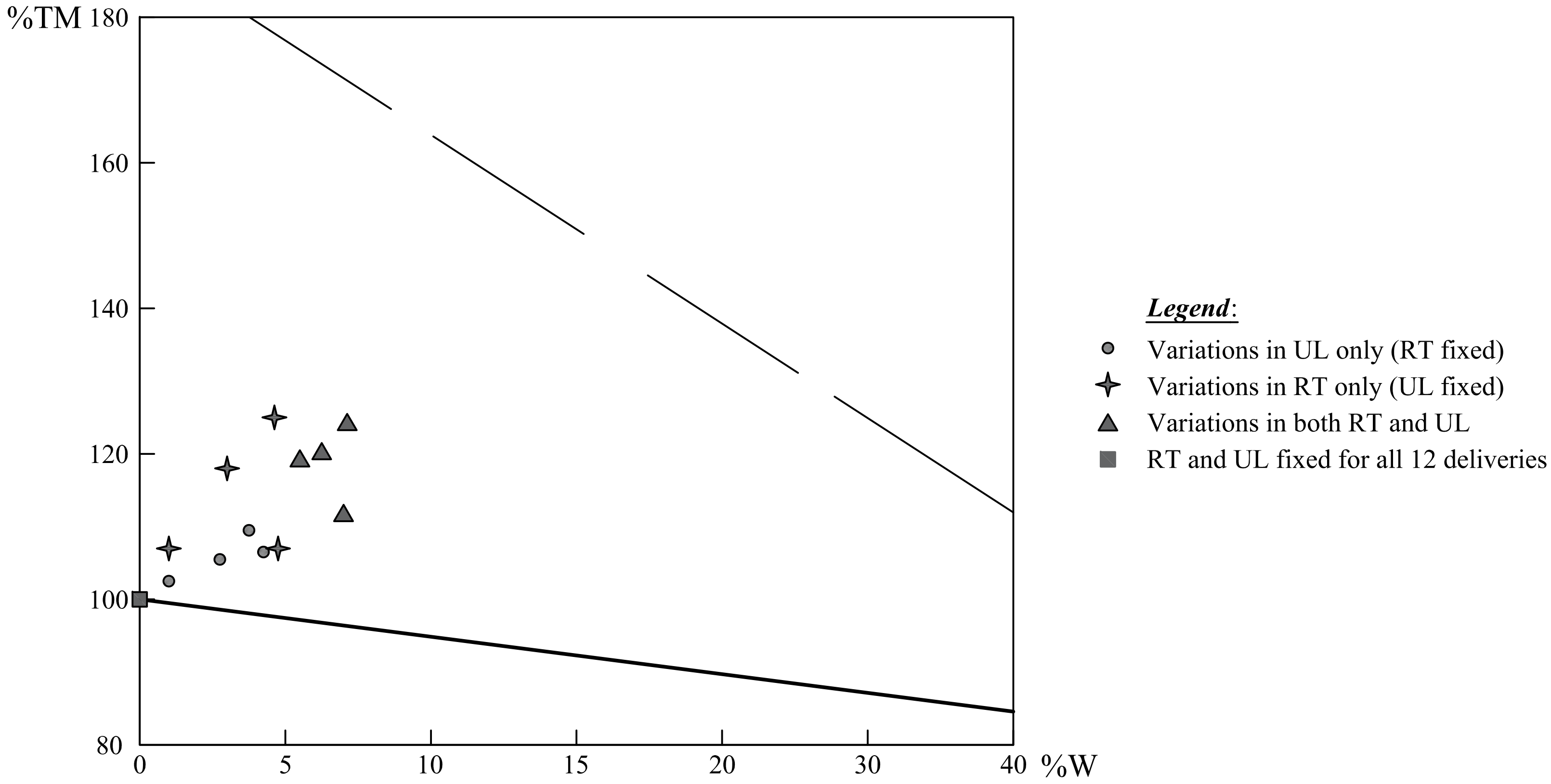

%TM
200
150
100
50
0
10
20
30
40
50
60
%W
A
B
C
D
E
N=3
RT/UL=3.33

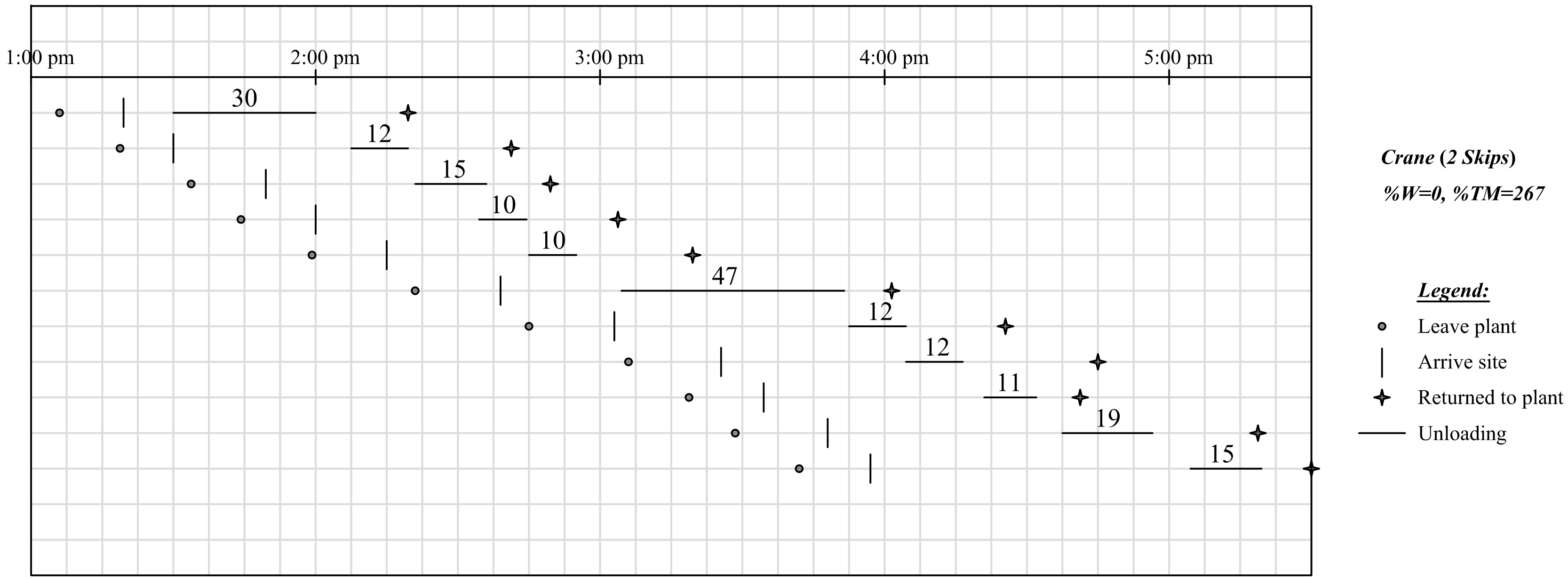


%TM
200
150
100
50
0
10
20
30
40
50
60
%W
N=3
RT/UL=3.33
A
B
C
D
E



%TM
200
150
100
50
0
10
20
30
40
50
60
%W
N=4
RT/UL=3.33
A
B
C
D
E


%TM
180
160
140
120
100
80
0
5
10
15
20
30
40
%W
Legend:
Variations in UL only (RT fixed)
Variations in RT only (UL fixed)
Variations in both RT and UL
RT and UL fixed for all 12 deliveries


1:00 pm
2:00 pm
3:00 pm
4:00 pm
5:00 pm
30
12
15
10
10
47
12
12
11
19
15
Crane (2 Skips)
%W=0, %TM=267
Legend:
Leave plant
Arrive site
Returned to plant
Unloading

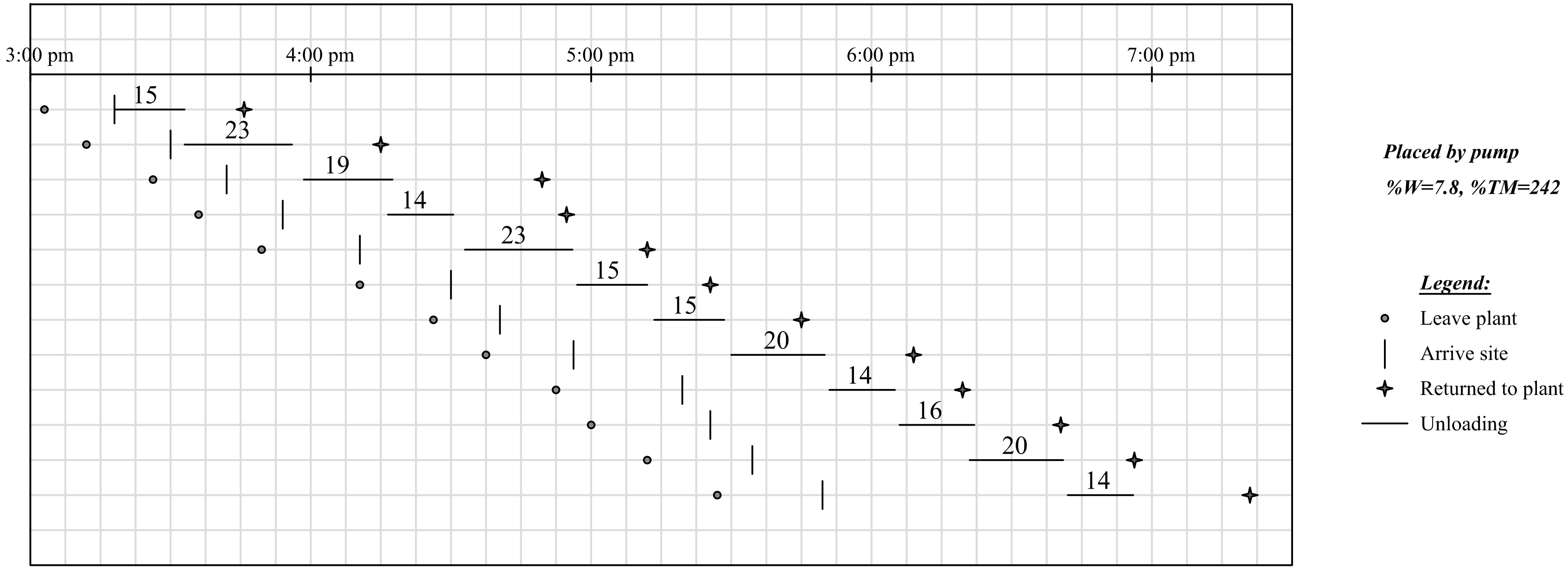

3:00 pm
4:00 pm
5:00 pm
6:00 pm
7:00 pm
15
23
19
14
23
15
15
20
14
16
20
14
Placed by pump
%W=7.8, %TM=242
Legend:
Leave plant
Arrive site
Returned to plant
Unloading

Table 1. Example of timing data for each truck (Pour 12)

Order pour size: 87 m^3				Actual size: 85 m^3		
Distance: 4 km				Placing method: Crane-2 skips		
Order Time: unknown				Arrival time required: 14:30		
Start to load	Leave plant	Arrive site	Begin unload	Finish unload	Leave site after washing	Back to plant
13:58	14:08	14:35	14:44	15:00	15:08	15:15
14:11	14:27	14:52	15:00	15:23	15:30	15:46
14:51	15:01	15:20	15:31	16:00	16:06	16:20
15:16	15:22	15:50	16:03	16:23	16:31	16:50
15:42	15:49	16:15	16:26	16:50	16:55	17:10
15:58	16:05	16:40	16:53	17:05	17:14	17:30
16:14	16:22	16:45	17:09	17:45	17:51	18:00
16:30	16:37	17:05	17:48	18:00	18:05	18:25
16:44	16:51	17:25	18:03	18:15	18:20	18:40
17:06	17:14	17:50	18:16	18:30	18:36	19:12
17:35	17:42	18:15	18:34	19:00	19:08	19:20
17:48	17:54	18:30	19:02	19:15	19:27	19:32
18:03	18:11	18:35	19:18	19:30	19:37	19:50
18:19	18:26	18:55	19:33	19:45	19:50	19:55

Table 2. Stages of study

Stage	Nature of study	Type of finding sought
A	Resource matching performance of the delivery system for a single pour is assessed. Each activity duration in the delivery cycle is fixed and remains the same throughout the pour for all deliveries.	The extent to which poor matching performance is a fundamental property of the system itself, and outside the control of the delivery scheduler.
B	As for Stage A, but some activity durations are lengthened to represent a delivery delay and/or a delay by the site crew in placing a delivery.	The extent to which significant, typical type of delay affect resources matching performance.
C	True stochastic nature of the activity durations is recognised. The stochastic effects are assessed on Stage A and Stage B performances.	The comparative influence on matching performance of the stochastic nature of real delivery activities.
D	Raw data delivery timings analysed, for a sample of real pours, in relation to pour performance.	The influences, if any, other than those identified in Stages A, B, and C.

Table 3. Sudden delay simulations (12 deliveries each pour)

Run parameters	i) N=3, RT=40, UL=25			ii) N=3, RT=40, UL=20		
	Pour time	%W	%TM	Pour time	%W	%TM
Steady state	300	0	135	240	0	100
1.Control	300	0	150	240	0	119
2.+40 min on UL6	340	0	168	280	0	145
3.+40 min on RT6	320	6	147	280	14	129
4.+40 on UL6, 8, RT6, 8	400	5	165	360	11	150
As 1, but stochastic	298	1	151	246	6	128
As 2, but stochastic	348	1	171	286	4	148
As 3, but stochastic	333	7	155	287	16	138
As 4, but stochastic	398	6	166	365	10	150
Stochastic RT,UL ranges	RT=28−52, UL=22−28			RT=28−52, UL=14−26		

Run parameters	iii) N=3, RT=40, UL=12			iv) N=4, RT=40, UL=12		
	Pour time	%W	%TM	Pour time	%W	%TM
Steady state	192	25	75	152	5	95
1.Control	192	25	86	152	5	122
2.+40 min on UL6	232	21	109	192	4	178
3.+40 min on RT6	232	38	90	192	25	150
4.+40 on UL6, 8, RT6, 8	312	28	127	272	18	192
As 1, but stochastic	204	28	93	158	7	132
As 2, but stochastic	234	22	116	190	9	176
As 3, but stochastic	230	37	86	190	25	136
As 4, but stochastic	295	24	116	270	17	181
Stochastic RT,UL ranges	RT=28−52, UL=9−15			RT=28−52, UL=9−15		

BIOGRAPHICAL DETAILS

[Author 1 bio]

Ir. Professor Mike Anson, now Professor Emeritus, obtained his Bachelor degree in Engineering Science at Oxford University in 1959 and his Ph.D in 1962 at Imperial College, London following research into theories of failure for concrete. After industrial experience in South Australia and research experience with CSIRO, Division of Building Research in Melbourne, he taught at the Dept. of Engineering, Lancaster University, UK for 17 years; as Head of Dept. for the last 6 of those. In 1988, he became Head of the Department of Civil and Structural Engineering at the Hong Kong Polytechnic, in 1992, Dean of the Faculty of Construction and Land Use and in 2001, Head of the Department of Building and Real Estate in the, by now, the Hong Kong Polytechnic University. He retired in 2003 and has remained active on a part time basis ever since. His research interests have merged concrete technology with construction management. The former includes concrete tanks design and early age strains in concrete walls. The latter, amongst others, includes the benchmarking of concrete placing in the UK, West Germany, and Hong Kong, and latterly the difficult problem of timing ready mixed concrete deliveries to sites so as to maximise the productivities of both site placing crews and truckmixer concrete delivery vehicles. He is a Fellow of the Institution of Civil Engineers and a Fellow of the Hong Kong Institution of Engineers. He can be contacted at: clanson@polyu.edu.hk

[Author 2 bio]

Ir. Thomas Ying is a chartered Civil and Structural Engineer. He participated in different Civil and Structural projects after receiving his Bachelor and M.Phil degrees in Civil and Structural Engineering from the Hong Kong Polytechnic University. He has been a Lecturer in the Department of Construction of Vocational Training Council, Hong Kong since 2009. He has been studying for his PhD degree with the Royal Melbourne Institute of Technology (RMIT), Australia and is scheduled to complete his study in 2018. His research interests include cost and safety management, building inspection and construction management. He can be contacted at: kc_ying@vtc.edu.hk

[Author 3 bio]

Dr. Francis Siu is currently an Assistant Professor of Construction and Real Estate Management in the Department of Building and Real Estate at Hong Kong Polytechnic University. He received his Bachelor of Engineering with Dean's honor (2009) and his Master of Philosophy (2011) from the Department of Civil and Structural Engineering at Hong Kong Polytechnic University. In 2016, he received his Doctor of Philosophy from the Department of Civil and Environmental Engineering at the University of Alberta, Canada. Later that year, he began a postdoctoral fellowship and served as an instructor in the Department of Civil and Environmental Engineering at the University of Alberta. His research focuses on developing innovative methods and technologies in the fields of project planning, control, and visualization. He is building upon previous industrial research experience, which he gained while collaboration with multiple construction companies in both Hong Kong and Canada to advance the knowledge and practice of building, infrastructure, and industrial construction. He can be contacted at: francis.siu@polyu.edu.hk