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Concrete placing crew and truckmixer productivities as affected by delivery scheduling policies

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ABSTRACT

When ready mixed concrete is placed in forms on site, the goal is to ensure that both the placing crew is never idle when waiting for a delivery of concrete and that concrete delivery truckmixers never have to wait in a queue to be unloaded. This situation is almost never achieved in practice for a routine pour. Usually, both crews and truckmixers have to wait for some of the time. To better understand the behavioural characteristics of the concreting system, in terms of crew idle time and truckmixer excess time on site, simulation experiments were carried out to compare the effects of two truckmixer plant dispatch policies. For larger pours in particular, a serial dispatch policy is found more wasteful of truckmixer time than circulating dispatch as long as the correct size of circulating fleet is chosen. In addition, for serial dispatch, due to the system flow parameter variabilities seen in real life, it is suggested that to choose the theoretically optimum dispatch interval at the plant is wasteful of truckmixer time and that better coordinated plant and site resource matching requires slightly greater choice over the length of intervals.

KEYWORDS Site concreting; concrete delivery scheduling; matching resources; concreting productivity; stochastic analysis
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1. Introduction

This article reports a research study related to the placing of ready mixed concrete in formwork on site. Of specific interest is the efficient use of the concrete placing crew and of the concrete delivery truckmixers based at the concrete mixing plant. The method used to assess efficiency was the performance of simulation experiments of the concrete delivery and placing process measuring inefficiency in terms of lost crew time and truckmixer provision or over-provision on site for a typical routine pour, allowing for the stochastic nature of the flow activity parameters of the simulation model. The model was validated against a database of 118 actual pours which included plant/site resource coordination performance in terms of crew and truckmixer productivity.

Lost crew time is represented by the parameter *%W*, the time spent by the crew idle, waiting for the arrival on site of the next truckmixer, expressed as a percentage of the total pour duration. Pour duration is defined as the time between the start of unloading of the first truckmixer delivery and the finish of unloading of the last delivery. When *%W*=0, the crew is never idle due to an unbroken supply of concrete to the site.

Truckmixer provision is represented by the parameter *%TM*, the sum of the times spent on site by truckmixers being unloaded plus the times spent idle waiting to be unloaded, also expressed as a percentage of total pour duration.

If *%TM*=100 when *%W*=0, ideal matching of resources has occurred. Truckmixers never wait in a queue on site and the placing crew are never idle.

In Figure 1, Anson et al. (2019; 2002) present a Hong Kong concreting industry benchmark measured 20 years ago based on 118 concrete pours, varying in size between 4 and 23 truckmixer deliveries (averaging 11 deliveries) and unloaded by various means, such as mobile and fixed concrete pumps, crane and skip, direct tipping and others. Each plotted point represents the *(%W*, *%TM*) performance combination observed for one pour, a measure of the resource coordination achieved for that pour between site management and concrete plant management. The *(%W*, *%TM*) variability across all 118 pours is very considerable, with a wedge-shaped distribution and very few pours close to the ideal coordination point of (0, 100). The simulation results below are consistent with such distribution and there are reasons to suppose that the form of Figure 1 would be reproduced in Hong Kong today and probably elsewhere. Unfortunately, there are no recently published data on concrete pours comparable to that of Figure 1, as far as the authors are aware, to confirm this statement or otherwise. The figure is the result of the inevitable variability which exists in regard to truckmixer journey times, truckmixer unloading times and dispatch intervals at the concrete plant, let alone major disruptions due to traffic jams or unexpected site problems which might involve, say, the temporary diversion of the concreting crane to another activity. The GPS systems installed nowadays on truckmixers and modern scheduling software aids can do nothing about these basic realities. The greater precision, due to GPS, ought to help somewhat to reduce scattering of the type shown in Figure 1, because plant dispatchers can be better informed about the locations of their fleet, but the fundamental wedge of Figure 1 would remain, but just a little slimmer perhaps if the degree of scattering of the plotted points is reduced. A study is needed to establish whether the use of GPS today has indeed brought about any such reduction in the distribution scatter.

Figure 1 provides the motive underlying the study, which is an attempt to explain, or understand, why the benchmark distribution is like this. How is the behaviour of the system affected by the durations and relative durations of the various flow parameters involved and the variability in those values? Understanding is a necessary step towards potential improvement in practice. In addition, two truckmixer dispatch policies have been compared in terms of their effects on the (*%W*, *%TM*) pairings. One is the serial dispatch mode normally seen in Hong Kong, with its very big capacity plants and consequent large number of truckmixers available at the start of the day. The other is a circulating dispatch policy where a designated set of truckmixers circulate between plant and site, making two or more deliveries each until the concrete order is fulfilled.

Although much research has been devoted to the study of concreting on site, no paper seems to have benchmarked resource coordination in the manner of Figure 1. Much research (see below) has concerned modelling the system and improving such models, including examples of simulation modelling and optimising models which attempt to improve some pour performance objective by optimising truckmixer delivery schedules. The latter aim is difficult to achieve since a trade-off exists between *%W* and *%TM*. Minimum *%W* is an objective of the site and minimum *%TM* would be preferred by the concrete supplier. Figure 1, however, demonstrates that lowish levels of both *%W* and *%TM* can be obtained in practice, representing well co-ordinated pours which are efficient from the point of view of both parties.

Performance benchmarking studies have also been conducted, for example, in regard to measuring the placing rates achievable for different systems of unloading and transporting concrete on site, such as mobile or fixed concrete pump, tower crane and skip, and others.

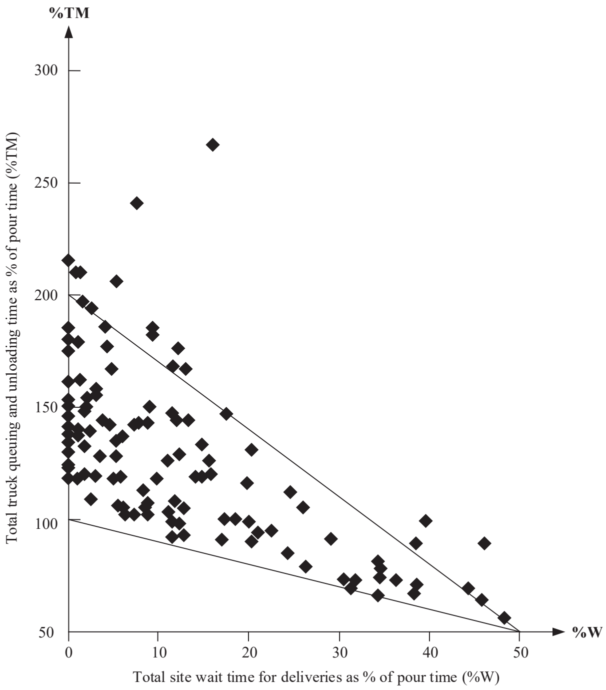

Figure 1. Site waiting vs truckmixer provision on site for 118 concrete pours.

2. Study objectives and contributions made

2.1. Objectives

1) To determine the extent to which (*%W*, *%TM*) outcome pairs for a concrete pour on site are affected by the degree of variability of the flow process parameters of truckmixer unloading duration, journey time between plant and site, roundtrip journey time, truckmixer dispatch interval at the plant and the pour properties thereof, distance between plant and site in terms of journey time and pour size in terms of the number of deliveries required.
2) To compare serial and circulating truckmixer dispatch policy outcomes to seek guidance on the circumstances, if any, when one of these policies might be better deployed in practice than the other. A circulating dispatch policy consists of a set of truckmixers circulating between plant and site until all deliveries have been made. Thus, a 12-delivery pour might be served by three truckmixers making four deliveries each. A serial dispatch policy, the norm in Hong Kong, is a scheduled list of pour deliveries made by a series of truckmixers, with no plan in general for any particular truckmixer(s) to circulate. A policy of circulating dispatch has the advantage that dispatch intervals at the plant are directly influenced by the concrete placing capacity on site. This promotes better resource matching and better resource utilisation, as long as the number of circulating truckmixers is correctly chosen (see below).

2.2. Contributions made

Past research work published by the authors includes the development of a pour process deterministic model, below, giving *%W* and *%TM*, in which the duration of each flow parameter is assumed to be fixed throughout the pour. For the study reported in this paper, that model was enhanced to enable study of the effects on (*%W*, *%TM*) pairs due to the real-life variability in durations of the flow parameters of truckmixer roundtrip time, truckmixer unloading time and the ratio of truckmixer dispatch interval at the plant/unloading time on site (i.e., to variabilities in RT, UL, and K respectively). Based on Monte-Carlo event ordered simulation studies, the enhanced model successfully predicts patterns of distribution and the magnitudes of (*%W*, *%TM*) pairs which are similar to those of the Figure 1 of real life. Insights into the behavioural characteristics of the system, as affected by system flow parameter variabilities, have been gained with implications for practical policies. One of these concerns the choice between serial and circulating truckmixer dispatch policies, a choice which significantly affects the utilisation of the placing crew and truckmixers. There is a qualified case that circulating dispatch should be the default option for large pours. The second relates to the discovery, in the case of serial dispatch, that increased flow parameter variability increases truckmixer queuing on site particularly acutely when *K*=1, the theoretical optimum, when the mean plant dispatch interval exactly equals the mean truckmixer unloading time on site, and therefore the interval likely to be normally opted for.

The contribution made towards understanding the reasons underlying observed system characteristics is unlike those contributions made by most other studies, which have been primarily concerned with improvements in system modelling based on simulation and schedule optimising models and with further benchmarking. The work of Weiszer et al. (2020), however, like the work described in this research study, was primarily concerned with system behaviour based on simulation experiments – in their case with the effects on placing crew and truckmixer downtimes of real-time regular routine feedback to plants on the number of truckmixers queuing on site and the consequent adjustment of the dispatch schedules at those plants.

3. Past research related to concrete delivery and placing

Many research studies have been completed over the last few decades on the efficient supply of concrete to sites and its placing in formwork. That body of research can broadly be divided into benchmarking studies, process simulation studies, and truckmixer scheduling optimisation studies. Samples of each type are given below.

3.1. Benchmarking

Benchmarking quantifies performance that is actually achieved in practice including, for example, the degree of coordination achieved between site and concrete plant management, which is central to this paper. Anson and Cooke (1988) benchmarked concreting productivities in a mainly rural area of the UK. Anson et al. (1994) and Anson and Wang (1998) benchmarked concrete placing performance on Hong Kong buildings, obtaining (*%W*, *%TM*) pairs for each pour. Anson et al. (2002) found that the matching of site resources and truckmixer provision was poor in 80% of cases. Lu and Anson (2004) utilised quality control records to benchmark different concrete placing methods in terms of m^3/hour and m^3/truckmixer-hour. Aziz (2017) formulated stepwise regression models to benchmark system performance using the metric actual work units/hr divided by expected *wu*/h for different segments of the process.

3.2. Simulation-based studies

Simulation mimics the workflows of concrete placing crews and individual truckmixers, allowing for variability in such parameters as mean dispatch interval, journey times and truckmixer unloading times on site. Dawood (1995) and Misir et al. (2011) developed heuristic truckmixer allocation rules to improve pre-cast concrete unit manufacturing plant utilisation. This is not strictly the type of system studied by the authors but is not dissimilar in that a construction site might be in the vicinity of a number of suitable batching plants from which to choose. The study concerned the optimum choice of manufacturing plant from which to accept precast unit deliveries. To minimise project costs, Smith (1998, 1999) and Dunlop and Smith (2002) studied the effect of truckmixer inter-arrival times on site on the utilisation rate of the site concrete pump and the downtime of truckmixers. For a given pour, they showed how to determine the inter-arrival rate of truckmixers which would result in minimum truckmixer queuing on site while still allowing for continuous pumping. They also noted that supplier costs were more sensitive than site costs to variations in inter-arrival times on site. This chimes with the finding of this research, above, that variability in dispatch interval at the plant affects truckmixer downtime much more than placing crew downtime. Zayad and Halpin (2001) studied productivity of a concrete batching plant as affected by such factors as the number of truckmixers based there and the space occupied by conveyors and hoppers. Sawhney et al. (1999) showed that petri-net modelling provides a viable analysis method. Specifically, given unlimited truckmixer availability, they showed how to determine the minimum number of truckmixers actually needed for a specific pour, assuming a continuous supply of concrete to the placing crew. Concrete delivery and placing simulation platforms, such as HKCONSIM (Lu et al., 2004), RMCDiSO (Feng et al., 2004) and RMCSIM (Tang et al., 2005), have been developed. These platforms are designed to facilitate simulation studies of multi-plant systems supplying to a multiplicity of sites on any one day. Misir et al. (2011) worked on the development of what they called hyper-heuristics when studying the very difficult problem of multi-plant multi-site truckmixer scheduling. Wang et al. (2001), as others above, also quantified the significant effects on the efficiency of the appropriate truckmixer inter-arrival times on site for a single pour. In their case the interest was to find what inter-arrival time on site to aim for, in the context of pumped pours in Singapore, which would provide a good standard of concrete placing productivity in general. They found the most appropriate inter-arrival time to be 11 minutes. Lu et al. (2004) and Tang et al. (2005) explored the effect of the number of truckmixers available on *%W* and *%TM*, and Park et al. (2011) found that durations of loading and unloading, positioning on site and slump test delays are critical productivity considerations. This is not at all surprising since these considerations directly affect the durations and variabilities of truckmixer effective travel durations and effective truckmixer unloading times, which are two of the key system flow variables represented in the authors' models below. The simulation model of Weiszer et al. (2020) was designed to test placing crew and truckmixer time wastage, as affected by simulated adjustments to the initial dispatch schedule in response to regular, "real-time" feedback on the number of truckmixers queuing on site. Their dispatch schedules were neither serial nor circulating, but amalgamations of the two.

3.3. Optimising studies

"Optimal" solutions relate to some chosen criterion, given either a simulation model base augmented by an optimisation algorithm, such as the genetic algorithm (Naso et al., 2004, 2007; Maghrebi et al., 2014), the particle swarm algorithm (Lu and Lam, 2005) and bee colony optimisation (Srichandum and Rujirayanyong, 2010), or a mathematical model (Yan and Lai, 2007; Yan et al., 2008; Asbach et al., 2009; Hertz et al., 2012; Liu et al., 2014) that sufficiently represents a concrete delivery system. Most researchers have focussed on truckmixer schedules. Naso et al. (2004, 2007), Yan and Lai (2007), Yan et al. (2008), and Liu et al. (2014) minimised delivery costs by varying the number of truckmixers scheduled, and Albayrak and Albayrak (2016) by supplying concrete to the site from several neighbouring batching plants and optimising the quantity of concrete supplied by each one. Lu and Lam (2005) minimised truckmixer and concreting crew idle times for a fleet of truckmixers with different concrete carrying capacities, by optimising the mix of truckmixer sizes deployed. Hertz et al. (2012) studied the determination of optimal delivery routes to minimise truckmixer travelling times. These researchers were possibly primarily interested in developing optimising model techniques to advance the progress of optimising modelling itself in the concreting delivery and placing field. The sub problems chosen, though all potentially useful in themselves, were possibly seen mainly as modelling "test beds".

These three classes of study all add to the understanding of a process which fundamentally encompasses competing site and plant performance objectives in practice. Site coordination performance has not usually been seen as a performance objective, at least not explicitly. Indeed, quite often the objective of some studies has related to plant resource performance alone. The site coordination criterion, the (*%W*, *%TM*) pair central to this paper, however, must surely be a criterion of relevance to all modellers of a process concerned with complete concrete delivery and placing operation. No specific pour is likely to be efficient unless there is good resource matching coordination between plant and site. This is a necessary condition, though not a sufficient condition.

4. System models central to this study

The study by Anson et al. (2019) introduced a deterministic model for a concrete pour with the outputs of *%W* and *%TM*. As stated above, the model comprises a serial dispatch component and a circulating dispatch component. A single unloading and placing crew is assumed and truckmixers are unloaded as soon as they arrive on site unless a previous truckmixer is still being emptied. Thus, strictly, a truckmixer has not "arrived" until site quality checks have been completed and site unloading time includes time spent in manoeuvring truckmixers onto the unloading point on congested sites.

The serial model system input variables consist of the number of deliveries required, *D*, and the parameter, *K*, the ratio of dispatch interval at the plant to the time, *UL*, that it takes to unload a truckmixer on site. *K* can be greater than, equal to, or less than, 1. The model assumes that the process variables, *K* and *UL*, take fixed values for a particular pour and that the first delivery is so timed that unloading starts as soon as a truckmixer arrives on site.

The serial model is expressed as:

$$\text{if } K>1: \quad \%W/100=(D-1)(K-1)/[D+(D-1)(K-1)];\ \%TM=100-\%W, \tag{1}$$

$$\text{if } K<1: \quad \%TM/100=1+(1-K)(D-1)/2;\ \%W=0, \tag{2}$$

$$\text{if } K=1: \quad \%TM=100;\ \%W=0. \tag{3}$$

If *K*=1, i.e., the dispatch interval is equal to the truckmixer unloading time on site, it can be readily seen that the first two equations both reduce to *%W*=0 and *%TM*=100.

Figure 2 is a graphical illustration of these equations. The formal proofs are given in Anson et al. (2019), but it is not difficult to accept the equations, since when *K*=1, the dispatch interval, and hence the inter-arrival time on site are identical to the truckmixer emptying time. Thus, as unloading finishes for one truckmixer, the next truckmixer arrives at the unloading point just in time. There is no waiting by the gang, nor by the truckmixers. When *K*>1, the second truckmixer clearly arrives at a time (*K*-1)*UL* after the first truckmixer has been emptied. That truckmixer does not have to wait to be unloaded but the crew has had to wait

$(K-1)UL$ minutes for that second truckmixer to arrive. This wait occurs for every delivery except the first, making a total crew wait time of $(D-1)(K-1)UL$ and a total pour time of $D(UL)+(D-1)(K-1)UL$. When $K<1$ the second truckmixer arrives at a time $(1-K)UL$ before the first truckmixer has finished unloading and must wait therefore for that long before it can start unloading. The crew, with no waiting, can start unloading the second truckmixer as soon as the first has been unloaded. The third truckmixer, however, arrives $2(1-K)UL$ minutes before the second truckmixer has been emptied. The fourth arrives $3(1-K)UL$ minutes too early and so on. Thus, there is never any waiting by the crew, but truckmixer total time on site is $D(UL)$ plus the sum of the *AP*, $1(1-K)UL + 2(1-K)UL + \ldots + (D-1)(1-K)UL$; this sum is $(1-K)UL$ times $D(D-1)/2$) and the pour time is $D(UL)$.

The circulating model system consists of the number of truckmixers, *N*, in the circulating set and the ratio RT/UL where *UL* is as above, and *RT* is the roundtrip circulating duration "leave site until return to site". This includes time spent refilling with concrete at the plant and any other type of delay affecting *RT* variability. Again, the variables *N*, *RT* and *UL* are assumed to be fixed for a particular pour in the case of the deterministic model. The model applies to "steady state" circulation. For the first batch of *N* truckmixer deliveries, serial dispatch would normally apply, with $K=1$. Site unloading capacity dictates the steady state circulation timing patterns of subsequent batches of *N* deliveries.

The circulating dispatch system is an example of a Balance Point Process (Halpin and Woodhead, 1974; Anson and Siu, 2019). A particular feature of a balance point process is that lost time cannot be zero for both production plant and servicing plant unless the cycle time for each server delivery is an integer multiple of the production time associated with each delivery. Thus, in our concreting case, the ideal situation when $\%W=0$ and $\%TM=100$, can only occur when the parameter RT/UL is exactly an integer. If $N=1+RT/UL$, both reduce to the ideal $\%W=0$ and $\%TM=100$.

The model is expressed as:

if $N<1+RT/UL$:
$$\%W/100=1-N/(1+RT/UL);\ \%TM=100-\%W, \quad (4)$$
if $N>1+RT/UL$:
$$\%TM/100=N-RT/UL;\ \%W=0, \quad (5)$$
If $N=1+RT/UL$:
$$\%W=0;\ \%TM=100. \quad (6)$$

Figure 3 is a graphical illustration of the model. Again, the formal proofs are given in Anson et al. (2019). After unloading, the first truckmixer will be back on site *RT* minutes later. During that time the crew is busy unloading truckmixers 2, 3, …, *N*, occupying a time of $(N-1)UL$. If $RT>(N-1)UL$, or $N<1+RT/UL$ in Figure 3, then the crew has to wait for $RT-(N-1)UL$ minutes before the first truckmixer is ready for its second unloading. Subsequent truckmixers arrive back on site at intervals of *UL* after the first in the set and each of those can be unloaded, therefore, as soon as they arrive. Thus, the second set *N* of deliveries suffers only that single wait by the placing crew followed by continuous activity until all N truckmixers have been unloaded. It is clear that this pattern repeats exactly for all subsequent batches of N deliveries. Thus, *%W* and *%TM* for the case $N<1+RT/UL$, are derived respectively from crew wait time $= RT-(N-1)UL$ and TM provision$=N\text{x}UL$ given the pour time of $RT-(N-1)UL+N(UL)$. Thus, $\%W+\%TM=100$ and *%W* simplifies to $100\ (1-N/(1+RT/UL))$. If, on the other hand, $RT<(N-1)UL$, or $N>1+RT/UL$ in Figure 3, then the first truckmixer arrives back on site before all *N* truckmixers of the first batch have been unloaded and has to wait on site for $(N-1)UL-RT$ minutes before it can be unloaded. Each subsequent truckmixer in the batch arrives on site *UL* minutes after the preceding truckmixer and also waits for $(N-1)UL-RT$ minutes. The placing crew never has to wait, so $\%W=0$ and pour time is $N(UL)$. Truckmixer provision is $N\ ((N-1)UL-RT)+N(UL)$ minutes. $\%TM/100$ simplifies to $N-RT/UL$.

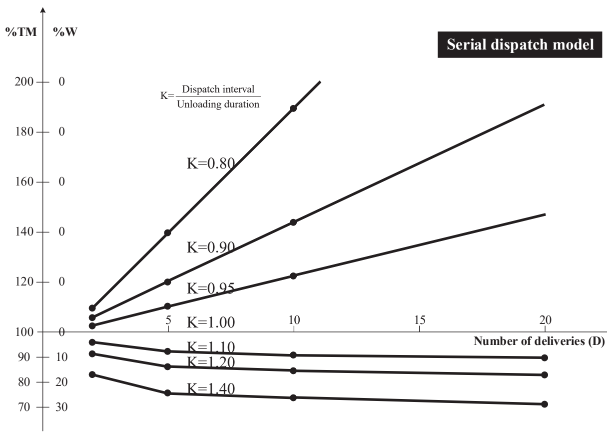

Figure 2. *K* and *D* effects on (*%W*, *%TM*) for serial dispatch.

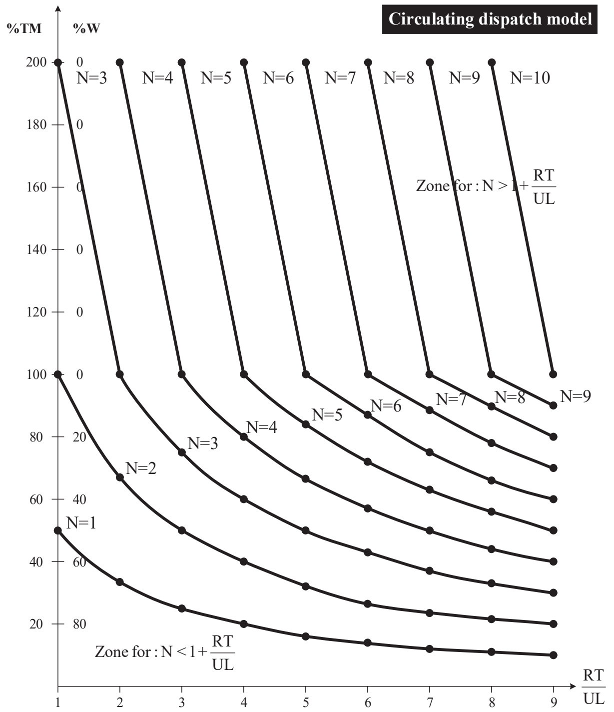

Figure 3. *N* and *RT/UL* effects on *%W*, *%TM* for circulating dispatch.

The *(%W*, *%TM*) coordinate pairs predicted by this deterministic model have the same magnitude of scatter as the real pours of Figure 1. Those pairs, however, scatter only along the *%W*=0 axis, the left-hand boundary of the Figure 1 wedge or along the *%W*+*%TM*=100 lower boundary of the wedge, as the equations make clear. The displacements of the real results, away from those boundaries which form the wedge-shaped distribution of Figure 1, are not predicted by the simple deterministic model.

Figures 2 and 3 reveal some behavioural characteristics of the above deterministic model of practical relevance to this study.

For serial dispatch, Figure 2 shows that if *K*<1, large *%TM* values of over 150 occur for large pours of over 20 deliveries even if *K* is as high as 0.95, close to the theoretical ideal of *K*=1, when the dispatch interval exactly equals the unloading rate on site. As *K* becomes smaller at 0.9, still quite close to the ideal, *%TM* becomes large for pours as small as 12 deliveries and unacceptably large as *K* decreases below 0.9, except for small pours of only a few deliveries. Conversely, if *K*>1, the *(%W*, *%TM*) predicted values are little affected by pour size. %W does increase steadily with an increase in *K* but much less dramatically, than the increases in *%TM* when *K*<1.

For circulating dispatch, according to the balance point theory proposed by Halpin and Woodhead (1976), it is essential to select the appropriate value of *N*. Figure 3, an augmentation of balance point theory by Anson and Siu (2020), shows that this appropriate *N* is dictated by the parameter *RT*/*UL*, if large values of *%W* or of *%TM* are to be avoided. In fact, unless *RT*/*UL* is exactly an integer (not the case in general) it is impossible to achieve the perfect coordination measure of *%W*=0 and *%TM*=100. As long as the most appropriate *N* is selected, however, for the particular *RT*/*UL* value applied, Figure 3 shows that when *N*>1+*RT*/*UL* there is much less likelihood of reaching the very high %TM values of serial dispatch seen in Figure 2, when *K*<1. If *N*<1+*RT*/*UL*, *%W* values are predicted that are no greater than those predicted for serial dispatch cases for *K* in the range 1.05 to 1.2.

5. Simulation experiments

5.1. Serial dispatch

Figure 4 represents the *%W* and *%TM* results for a pour of 18 serial mode deliveries, with 20 different combinations of dispatch interval and parameter variability patterns. *D* was arbitrarily chosen as 18, as representative of the typical big pour. The largest in the Figure 1 sample was 23 deliveries. The average number of deliveries was 11. The process simulated consisted of time of dispatch from the plant, time of arrival on site ready for unloading, time of the start of unloading and time of the finish of unloading. If the preceding truckmixer was still being unloaded on arrival on site, or was in a queue waiting to be unloaded, the truckmixer would start a queue or join the existing queue. Otherwise, it would immediately start to unload. The simulation ended when the last truckmixer had been unloaded, giving the total pour duration. A running total was maintained during the simulation, of the total time spent idle by truckmixers queueing and the total time spent by the placing crew idle, waiting for truckmixer arrivals.

The average *UL* for the simulations was taken as 20 minutes and the average journey time to site, *J*, was also 20 minutes. Each simulation run had its own unique combination of average *K* and average degree of variability (or "roughness", used below) about the mean *J*, *UL* and *K* values. The plotted *%W* and *%TM* pairs for each simulation experiment are the averages of 25 runs. The range of effects was explored for *K*=0.95, 1.0, 1.05, 1.1 and 1.2, each one combined with a roughness of 0%, 10%, 25% and 50%. Those pours with a mean *K* value of 1.0 had a mean dispatch interval equal to *UL* at 20 minutes. Pours with mean *K* values of 0.95, 1.05, 1.1 and 1.2, had mean dispatch intervals of 19, 21, 22 and 24 minutes respectively. 25 simulation runs were made for each case as this number was found sufficient to allow discrimination between the means of the different sets of *(%W*, *%TM*) pairs applied each time and to plot behavioural trends. The absolute precision to be obtained by making 1,000 simulations, say, is not necessary.

Pours with a roughness value of 0% conformed to the deterministic model above. Note that all such points of zero roughness lie on the wedge boundary of Figure 4, as explained above. Note also that the parameter *J* does not appear in the simple deterministic model above. Journey length, when constant, has no effect on *%W* and *%TM*, since the inter-arrival times on site exactly equal the dispatch intervals at the plant. This is no longer the case when J is treated as a stochastic variable.

A roughness value of 10%, is a variability of 10% about the mean *UL*, the mean *J* and the mean dispatch interval. Since 10% of 20 minutes is 2 minutes, the simulated *UL* and *J* values were chosen randomly between 18 minutes and 22 minutes with any value in that range being equally likely (i.e., uniform distribution assumed within the range) on each run. *UL* and *J*, therefore, would only be identical by coincidence. Similarly, the dispatch interval would vary about the intended value within a range of -2 minutes to +2 minutes. Thus, when *K*=1.1, the dispatch interval range would be 20–24 minutes. Uniform distributions were assumed because the data from the 118 actual pours indicated that nothing more sophisticated could be justified. For a pour of 11 deliveries (the average), the 11 values of *UL*, for example, would be spread across the range of values but with no observable pattern. There was no reason to assume, say, that a triangular distribution or a normal distribution was a better fit. Of course, the effect on the distribution of the final outputs for any simulation run, of three successive samplings of uniform distributions (the dispatch interval, the journey to site and the unloading duration) is far from uniform, with a large proportion of the results towards the middle of the range and fewer towards the extremes. The trends exhibited in Figure 4 are likely to be little affected by the adoption of one of the theoretical distributions. This is similarly the case for Figures 5-9, below.

In a similar manner to that of the 10% roughness case, a roughness of 25% corresponds to a range of -5 minutes to +5 minutes. *UL* and *J* varied between 15 and 25 minutes. A roughness of 50% means that *UL* and *J* varied between 10 and 30 minutes and dispatch intervals between 10 minutes less than planned and 10 minutes more than planned.

Table 1 summarises the ranges simulated in producing Figure 4 and gives the values of (*%W*, *%TM*) plotted. As stated, *D*=18 for all pours.

5.2. Circulating dispatch

Figure 5 represents the *%W* and *%TM* results for simulations of a pour served by a set of circulating truckmixers. As for serial dispatch above, the pour received 18 deliveries and had the same average *UL* value of 20 minutes and the same average journey time to site, *J*, of 20 minutes. The simulation assumed that the return journey to plant was also 20 minutes. It was assumed that the truckmixers return to plant for reloading concrete for the next delivery took place immediately (batching plants in Hong Kong are usually large with multiple concrete loading "legs"). The value, *RT*, therefore, consisted of the sum of the journey out, the journey back and a fixed allowance of 5 minutes for reloading with concrete. Note that for practical

Table 1. *K* and flow variable roughness effects on *%W* and *%TM* for serial dispatch.

	Simulated ranges (Minutes)			Performance	
K	*DI*	*UL*	*J*	*%W*	*%TM*
0.95	19 , 19 17 , 21 14 , 24 9 , 29	20 , 20 18 , 22 15 , 25 10 , 30	20 , 20 18 , 22 15 , 25 10 , 30	0 0.5 2.2 5.8	140 150 166 191
1	20 , 20 18 , 22 15 , 25 10 , 30	ditto	ditto	0 1.2 4.1 5.5	100 117 136 182
1.05	21 , 21 19 , 23 16 , 26 11 , 31	ditto	ditto	4.8 4.9 5.9 9.5	95 100 121 154
1.1	22 , 22 20 , 24 17 , 27 12 , 32	ditto	ditto	8.6 9.3 9.2 11.8	91 93 106 136
1.2	24 , 24 22 , 26 19 , 29 14 , 34	ditto	ditto	15.9 15.4 16.1 17.5	84 85 90 110

survey work the journey out time includes washing down at the plant after loading up and any quality checks on site. The journey back time includes washing down on site after unloading and any "friction" time at the plant before loading up. Each simulation had its own unique combination of average *RT*/*UL* and average degree of roughness about the mean values. The first set of truckmixers was dispatched at fixed intervals of *UL*. The effects on *%W* and *%TM* were explored for *RT*/*UL*=2.0, 2.2, 2.4, 2.6 and 2.8 and roughness values of 0%, 10%, 25% and 50%, for each *RT*/*UL* case, for a set of *N*=3 circulating truckmixers. Figure 5 also includes the results for *N*=4 circulating truckmixers for the *RT*/*UL* cases of 2.4, 2.6 and 2.8. This is because, for *RT*/*UL*=2, ideal coordination is given by *N*=3 and for *RT*/*UL*=3, by *N*=4.

The plotted simulation results in Figure 5 are the averages of 15 runs – fewer than the 25 for serial dispatch runs because the scatter is less in the case of circulating dispatch (see below). 15 simulations proved sufficient for system behaviour identification and for good enough approximations for *%W* and *%TM*. To save space, a similar table to that supporting Figure 4 is not shown.

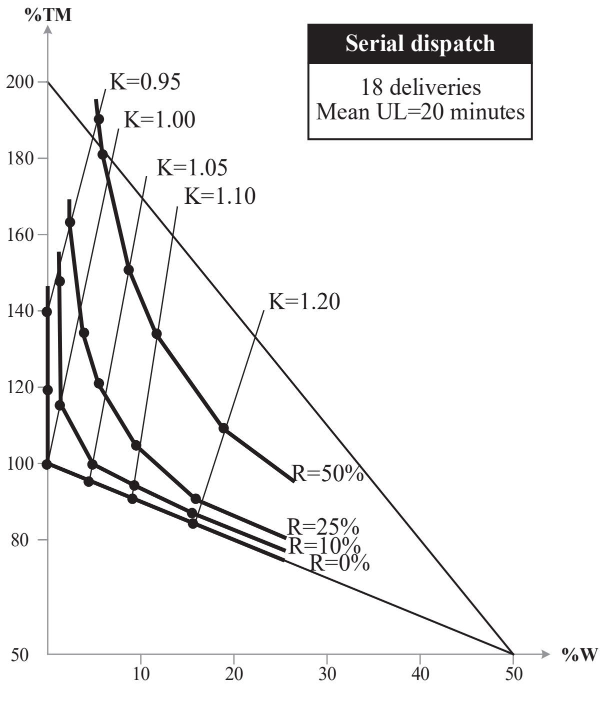

Figure 4. *K* and other variability effects on (*%W*, *%TM*) for serial dispatch.

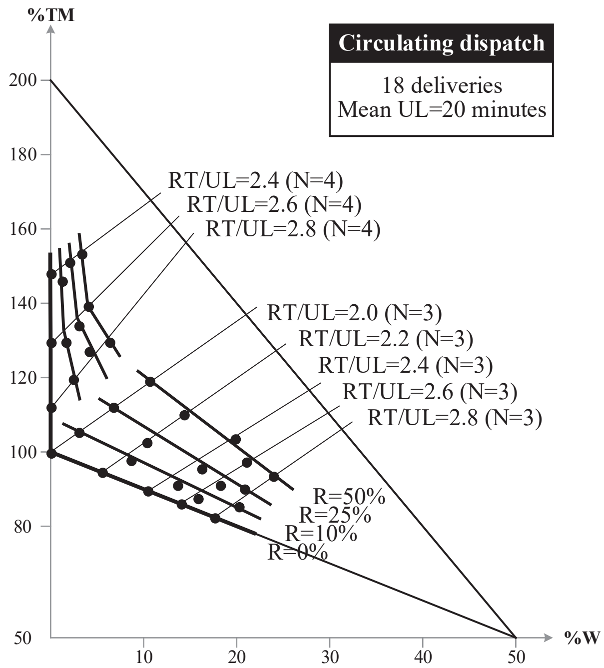

Figure 5. *RT*/*UL* variability effects on (*%W*, *%TM*) for circulating dispatch.

6. Experiment findings

6.1. Serial dispatch simulations of Figure 4

The Figure 4 serial dispatch range of possible outcomes, even for this single pour, is large in relation to the dimensions of the wedge, though predominantly confined to the left-hand half. Roughness is seen to have the expected negative effect on productivity, since increased roughness moves all points further away from the perfect point of (0, 100). The lines of equal *K* tend, strikingly, towards the vertical as roughness increases, meaning that *%TM* increases much more than *%W* for all values of *K*. Thus, roughness affects truckmixer downtime much more than crew downtime. This is a significant system behaviour observation of potential importance to plant managers. This observation serves to confirm the similar observation by Smith (1999).

Interesting also is that *%TM* increases from 100 to 180 if *K*=1, as roughness increases to 50%. But if *K*=1.1, *%TM* increases from 90 to only 135 for the same increase in roughness. The system therefore is more sensitive to roughness if the theoretically ideal value of *K*=1 is chosen by the plant, giving an increased risk of excessive truckmixer queuing on site. Opting for *K*=1.1 instead, is likely to result in much less truckmixer queuing on site. *%W* then becomes 12% instead of the 6% with *K*=1.

50% roughness, in fact, is not an improbably high figure. A sample of 15 real pours revealed average roughnesses of 30% for *J*, 47% for the dispatch interval and

42% for *UL*. The ranges about these averages for the 15 pours, were 17-50%, 25-70% and 13-60% respectively.

The Figure 1 data almost certainly relate to serial dispatch pours, as serial dispatch is overwhelmingly the normal policy adopted at plants in Hong Kong.

Since, in practice, *K* will sometimes be greater than the maximum of 1.2 simulated here and because there will sometimes be significant disruptions in journey times and unloading times, not simulated here, it is not surprising that the right-hand portion of the wedge of Figure 1 is also occupied, though rather more sparsely than the left-hand side.

The pours of Figure 1 averaged 11 deliveries. When *K*<1, the model of Figure 2 indicates that *%W* and *%TM* reduce linearly with pour size. A *%TM* figure of 180 for 18 deliveries reduces to about 150 for 11 deliveries, for *K*=0.9, and zero roughness. When *K*>1, however, there is a negligible pour size effect on the expected *%TM* and *%W* performance values.

6.2. Circulation dispatch simulations of Figure 5

In the case of circulating dispatch, the model equations show that *%W* and *%TM* values relate only to *N*, the size of the circulating fleet and to *RT*/*UL*. There is no pour size effect and Figure 5 holds for a pour of any size. When roughness equals 0%, the (*%W*, *%TM*) coordinates lie only on the boundary of the wedge, but it should be made clear that those plot locations are not precisely those of the ideal steady state models, because the first set of truckmixer deliveries, of the 18 made in total, were dispatched at intervals of UL, before steady state circulation was achieved. This might be the natural start to a circulating dispatch pour in practice.

As roughness increases for all values of *RT*/*UL*, the performance plots generally move further away from the ideal (0, 100) point with both *%W* and *%TM* increasing. Even so, with *N*=3, the high *%TM* values of serial dispatch are not seen, although *%W* does become unacceptably larger than 16% when *RT*/*UL* take the values 2.6 and 2.8. If at these ratios the decision to make *N*=4 had been made, larger *%TM* values would be obtained, but still less than 140% and *%W* does not exceed 8% even for roughnesses of 50%. Thus, an *N*=3 strategy for *RT*/*UL*=2.0, 2.2 and 2.4 and *N*=4 for 2.6 and 2.8, even for roughnesses at 50%, gives *%TM* and *%W* values not greater than 140 (usually much less) and 16 respectively. (This statement is only not true in the case of *RT*/*UL*=2.4 at the roughness level of 50%, where *%W*=20 and *%TM*=105 with *N*=3. If four truckmixers had been used instead, *%TM* would be 155 and *%W*< 5.)

6.3. Influence of pour distance on the findings of Figures 4 and 5

The simulation studies of Figures 4 and 5 assumed pours a distance of 20 minutes from the plant. Figure 6 gives the result of serial dispatch simulations to check the effect of pour distance on (*%W*, *%TM*) outcomes. For the same roughness of dispatch interval, average inter-arrival times on site will be greater the longer the journey time, given the same journey time roughness. As viewed from the site, extra journey time is similar, in effect, to the same journey time, but one with extra roughness. Figure 4 suggests, therefore, that the longer journey time should produce increased *%W* and *%TM*. Figure 6 supports this reasoning in that the mean 35-minute journey does indeed give rise to larger *%W* and *%TM* values than the mean 15-minute journey for the same *K* and roughness values. Both journeys were assigned a roughness value of 25%. The simulations also assumed a mean *UL* of 20 minutes with a roughness of 25%.

For the case of circulating dispatch, in Figure 7, (*%W*, *%TM*) values for *RT*/*UL*=4.0, 4.2, 4.4, 4.6 and 4.8 for the case of *N*=5 circulating truckmixers, are compared with the results for 2.0, 2.2, 2.4, 2.6 and 2.8 with *N*=3. Thus, one site is about twice as far away from the plant as the other. The roughness values for all runs were 25%, both for journey times and unloading times on site. As for serial dispatch, the effect of distance is an increase of *%TM*. There is little or no effect on *%W*.

This point is of some relevance to Hong Kong. In recent decades the trend has been towards ever larger plants and concentrations of truckmixers and greater average travel distances, therefore, to sites.

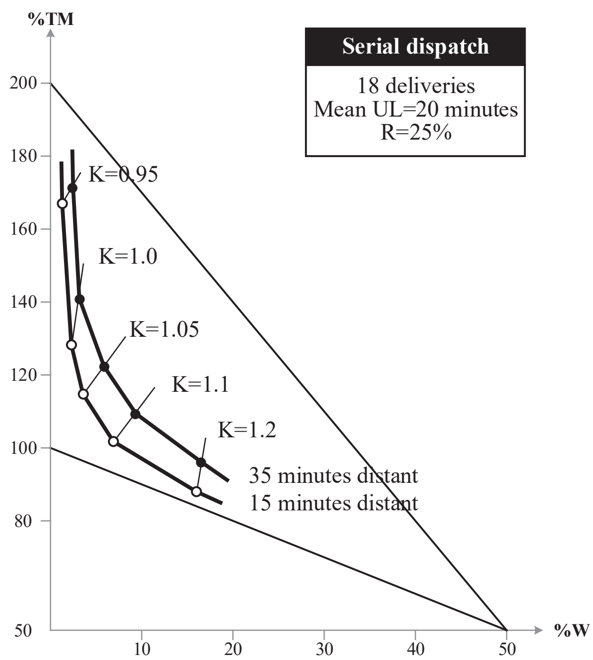

Figure 6. Effect of plant–site distance on (*%W*, *%TM*) for serial dispatch.

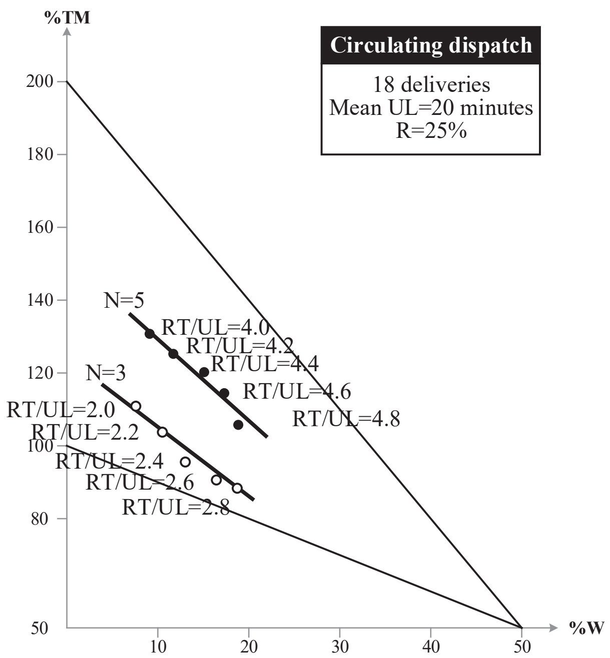

Figure 7. Effect of plant–site distance on (*%W*, *%TM*) for circulating dispatch.

7. Comparing circulating and serial dispatch policies

For a pour of 18 deliveries, Figure 5 presents a distribution showing lower maximum *%TM* values than those of the serial dispatch alternative shown in Figure 4. As deduced from Figure 2, however, the high *%TM* values of Figure 4 would reduce linearly with pour size for those cases when *K* is <1, so the extra efficiency of the circulating dispatch policy, in terms of *%TM*, is only significant for larger pours of, say, at least 12 deliveries; the value of *D* in Figure 2 where *%TM* reduces to about 150, for *K*=0.9. From Figure 3, circulating dispatch values of *%TM* can reach 150, but not more, as long as the correct value of *N* is chosen.

Based on the evidence of this study, therefore, it can be inferred, for larger pours, that a circulating dispatch policy should result in significantly less truckmixer time wasted as long as *N* is appropriately chosen. There is no parallel consequential increase in wasted placing crew time since the higher *%W* figures are much the same whether the dispatch policy is circulating or serial. In practice, however, if *K* is allowed to exceed 1.2, serial dispatch will give *%W* values which are unacceptably higher, at >20%, than those likely with circulating dispatch.

It is tempting to propose, therefore, that for larger pours the default policy should be one of circulating dispatch. This would be the proposition indeed if the appropriate value of *N* can be reliably chosen. This depends, however, on the *RT*/*UL* mean value being accurately predicted before the pour starts. If this is not possible the wrong N might be selected and a glance at Figure 3 shows that larger values than expected of *%W* and *%TM* may then result.

An advantage of circulating dispatch over serial dispatch is the fact that the actual *(%W*, *%TM*) performances achieved on a pour, are likely to be closer to the values aimed at. This is simply because truckmixer loadings and dispatches at plant are more effectively synchronised with operations on site. Figures 8 and 9 illustrate this point very clearly. Serial and circulating dispatch pours of 18 deliveries were simulated, both pours having the same roughness factor of 50%. Based on each of these figures, every one of 15 *(%W*, *%TM*) simulated pair results is plotted. The averages of all 15 are also shown. It is clear that the degree of scatter about the average is much less in the case of circulating dispatch. Indeed 10 of the 15 runs are very close to the average.

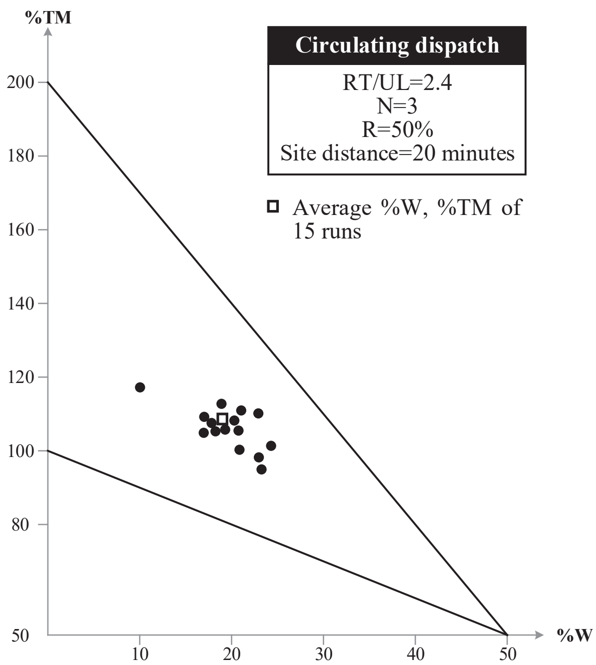

Figure 8. Range of 15 simulated (*%W*, *%TM*) possible outcomes (circulating dispatch).

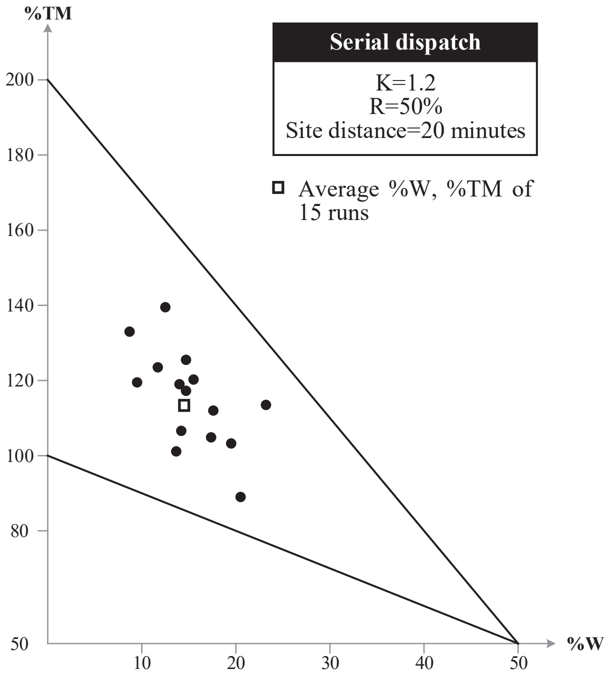

Figure 9. Range of 15 simulated (*%W*, *%TM*) possible outcomes (serial dispatch).

8. Case studies

Some experiments were then made to compare the measured (*%W, %TM*) values for five real serial dispatch case study pours, with the (*%W, %TM*) values to be expected if circulation dispatch had been the delivery policy instead. Figure 10 shows the (*%W, %TM*) performance plots of both the real pours and the simulated pours. The five real pours were taken from the 118 pour dataset of Figure 1. Two pours were selected with high *%TM* values, two with high *%W* values and one typical pour of average size at the centre of the Figure 1 distribution.

Table 2 gives the number of deliveries and the roughness information which applied to the five real pours. The fleet sizes, *N*, for the circulating dispatch simulations are also shown in Table 2, as are the assumed *RT*/*UL* ratios. The simulated mean roundtrip time was based on twice *J* plus allowances for loading with concrete at the plant and other activities including truckmixer washing downtimes. The simulated journey times comprising *RT* were all given the same roughness range as the journey to site time, *J*, of the real pours. Simulated *UL* durations were given the same roughness ranges as those of the real *UL*s.

Table 2. Variability ranges of the five case study pours of Figure 10.

Pour No.	*D*	*J*	*UL*	*DI*	*N (RT/UL)*
1	10	7 , 11	10 , 35	11 , 33	2 (1.2)
2	15	11 , 25	12 , 26	7 , 31	3 (2.7)
3	18	9 , 42	13 , 33	5 , 32	3 (2.2)
4	14	30 , 48	8 , 28	15 , 60	5 (4.6)
5	14	10 , 15	11 , 25	10 , 36	3 (2.2)

The results are striking. Real Pours 2 and 3 suffered from excessive truckmixer overprovision. Circulating dispatch reduced that overprovision very considerably to more normal levels of under 150%, but the crews then had to wait for 22% and 15% of the pour time, respectively. On Pours 4 and 5, the placing crew unacceptably waited for 46% and 28% of the pour time. Again, circulating dispatch reduced these excessive waits, to 30% and 15% respectively at the price of extra, but not excessive, truckmixer provision to the pours (30%, nevertheless, is still too big a wait). Perhaps simulated Pour 4 should have been served by a fleet of six truckmixers, given an *RT*/*UL* of 4.6, as indicated above in the discussion of Figure 5. Only for Pour 1 did the circulating dispatch policy produce a poorer result then the real result. This pour, however, was of only 10 deliveries and, as above, it is only for the larger pours that roughness effects cause serial dispatch to become particularly wasteful of truckmixer time.

Finally, it is notable that the five circulating dispatch results are closely concentrated, in comparison with the wide dispersion of the five serial dispatch results. This reinforces the observation, above, that wider use of circulating dispatch, as long as *N* is correctly chosen, might help to reduce the number of extreme outcomes, that is, outcomes situated at the upper left corner of the Figure 1 wedge, of excessive truckmixer provision, and at the lower right hand corner of the Figure 1 wedge, of excessive waiting by placing crews for concrete deliveries.

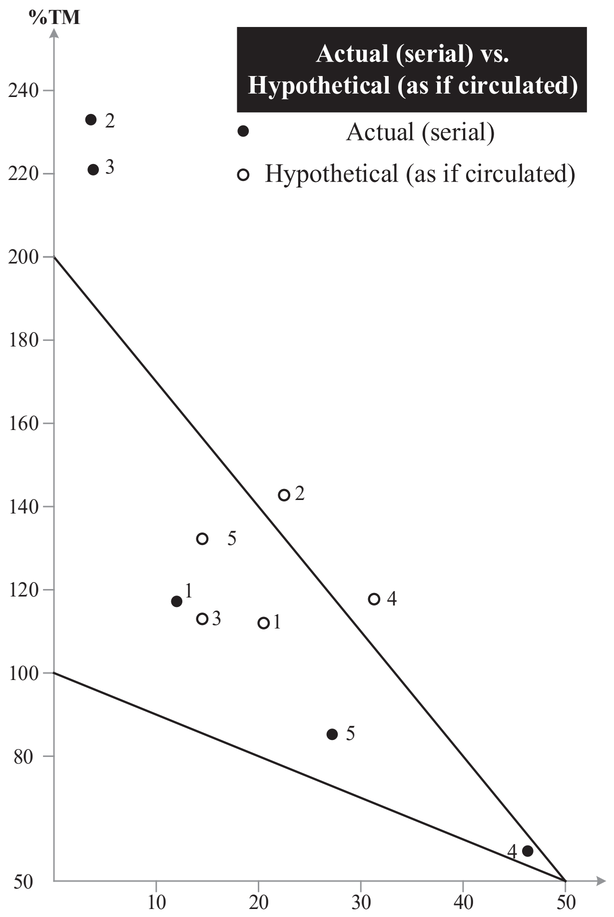

Figure 10. Five case study pours (actual serial dispatch vs. hypothetical circulating dispatch).

9. Practical factors affecting plant schedulers

Especially when *N*>1+*RT*/*UL* for circulating dispatch, it is clear from the slopes of the lines in Figure 3, that high values of *%TM* can result if *N* is not correctly chosen. For a larger pour, the advantage gained in dispatching trucks from the plant at intervals which match site production rates, might be cancelled out by the wrong choice of *N*. In fact, it is not easy to get this right. With their best efforts, site and plant managers might decide, say, that *UL* will average 24 minutes and RT will average 72 minutes, or *RT*/*UL* is 3.0. *N* is chosen as 4, therefore, giving *%W*=0 and *%TM*=100. In practice such estimates, even if very carefully considered, could easily be wrong by 10% or more. The actual average *RT*/*UL* value, for instance, could easily be about 3.6 at one extreme and 2.5 at the other. With four truckmixers, the simple model predicts *%W* to be approximately 10 in the one case and *%TM* to be 150 in the other. This analysis makes clear that some good degree of accuracy must be achieved in estimating *RT* and *UL*.

The wide scattering of the performance averages of the simulation results illustrated in Figures 8 and 9, also illustrates how hard it is for plant managers and site managers to achieve a specific coordinated performance goal for a particular pour. Since each point represents a potential real pour result and assuming the simulated variabilities are not too dissimilar to those that apply in practice, the outcomes of our real pour might lie anywhere within the range of the scattering shown. The chances of getting close to any target average (*%W*, *%TM*) are clearly not at all good in the case of serial dispatch, but they are better in the case of circulating dispatch.

Thus, although these simulation studies have revealed something about how the system behaves, which is of potential value to site and plant managers, it is of little direct help in the scheduling of individual truckmixer dispatches to a particular pour, because of the wide degree of inherent scattering about the (*%W*, *%TM*) system average, particularly in the case of serial dispatch.

Knowledge of system behaviour, however, remains relevant for general policymaking purposes because:

a) Of potential use in practice is the significant system behaviour finding, in the case of serial dispatch, that increased roughness leads to a rapid increase in *%TM* but only a small corresponding increase in *%W*. Of particular interest is the discovery that this undesirable effect is most marked when *K*=1, which is the ideal choice theoretically. This would indicate that plant managers should aim at dispatch intervals of about 10% to 15%, say, greater than the assumed site *UL* duration. A sensible policy might be expressed, perhaps: "to avoid excessive truckmixer queuing on site, dispatch intervals should never be less then *UL*, and average approximately 1.1 *UL*".

b) The study has demonstrated that parameter variability (roughness) about mean journey durations, dispatch intervals and unloading durations on site significantly moves the positions of (*%W*, *%TM*) pairs within the wedge and further away from the ideal performance point of (0, 100). The more the roughness the more the movement. In fact, the movements are not excessive if roughness is less than 25% (Figure 4) even when *K*=1. This insight, if understood by plant schedulers and site managers is potentially of practical use, because a 25% max variability about a mean *K* and mean *UL* may not be an unrealistic target to deliberately aim at. Journey times are less under control.

10. Study limitations

a) The study findings all derive from a programme of Monte-Carlo simulations and relate only to that specific model system. The extent to which the system mirrors the real system depends on how closely the flow model represents real activity flows. The system model can be further studied in

Anson et al. (2019). The fundamental assumption is that the journey to site concludes with immediate unloading, if the previous truckmixer has already been emptied; otherwise it joins a queue to unload. The truckmixers all unload in sequence at the one location; there are no parallel unloading points. Nevertheless, although the simulation model is simplified to only the flow variables dispatch interval *K*, *J*, *RT* and *UL*, the many detailed flow variables actually involved are components of one or other of these "hammock" variables. For example, on a congested site, the variable *UL* would embody the time involved in any complex truckmixer manoeuvring onto, and off, the unloading point. The roundtrip time variable, *RT*, embodies such matters as traffic congestion delays, the hosing down of truckmixers and site concrete quality checks.

b) During simulations, as stated, selected durations were all equally likely from within the range under test. It is not imagined that distributions in practice are fundamentally uniform, though there was no good reason to assume anything else in this study, but the experimental trends observed are not likely to be much affected by using more refined distributions.

c) The main simulation studies relate to pours of 18 deliveries only. Circulating dispatch results are not pour size dependent, but this is not true of serial dispatch. The serial dispatch fundamental model equation, through the size variable *D*, gives the effect of pour size on *%W* and *%TM* for a 0% roughness. The size effect trend at 0% roughness will surely be approximately replicated for roughness values of 10%, 25% and 50%, but the effect ought to be properly quantified with further simulations.

d) Finally, a single variability range was applied to all variables on each simulation run. Thus, if *UL* had a variability range, or roughness, of 25%, then so did the dispatch interval and so did the journey time to site. Since the experiments encompassed ranges of 0%, 10%, 25% and 50%, more complex combinations of variable roughness levels would provide additional plotted points, but probably interpolations only amongst those of Figures 4 and 5.

e) Though not exactly a limitation of the study, it should be pointed out that an objective of a plant manager, in general, may not necessarily be to minimise the wastage of truckmixer time, as assumed throughout the above study! If the system as currently practised, is wasteful of truckmixer time in general, then the cost of that wastage will have been automatically built into the price per cubic metre of concrete delivered. It is generally the case that the site contractor wants his pours to be placed as expeditiously as possible and the plant manager can perhaps be excused for wanting to keep his customer happy in that respect at the cost, if necessary, of an overprovision of truckmixer time. The ready mixed concrete industry is perhaps quite happy to sell concrete at its "proper basic" cost plus, in effect, the cost of the extra truckmixer time too, if the contractor is willing to pay for it. The industry can make a profit from both components via the concrete price actually charged.

11. Conclusions

In pursuing the two objectives, much of value has been revealed about the behaviour of the concreting system as affected by flow parameter variability and the extent to which the policies of serial dispatch and circulating dispatch differ in their effects on crew and truckmixer lost time.

Whether serial or circulating dispatch, the simulations demonstrate that significant effects on placing crew idle time and truckmixer total provision on site, are due to the variability of the mean values of the pour system flow parameters. The distribution, or scatter, of the real-life (*%W*, *%TM*) coordinates of Figure 1 are reproduced by the simulations, suggesting that pour parameter variability factors alone can explain the distribution to a significant extent. That a single big interruption in concrete supply or a big holdup on site, also contributes, has been reported already in Anson et al. (2019).

Four levels of variability, ranging up to 50% about the mean, were explored for their effects on the outcomes of both serial and circulating truckmixer dispatch policies. For serial dispatch, *K* value simulations ranged between 0.95 and 1.2. For the circulating dispatch alternative, *RT*/*UL* values ranged between 2.0 and 2.8 for three circulating truckmixers and 2.4 to 2.8 for four truckmixers. The effect of additional distance between concrete plant and site results in more lost time for truckmixers, regardless of the mode of dispatch and for the placing crew also in the case of serial dispatch.

For serial dispatch, the effect of increasing parameter variability is the increase of *%TM* quite steeply for all values of *K*, with quite small increases in *%W*. This steep increase in *%TM* is particularly marked when *K*=1, the very dispatch interval which is to be preferred as the most efficient, if all activities were to run smoothly on schedule. This severe effect on *%TM*, when *K*=1, which is something of a discovery, suggests that plant managers should aim to ensure that dispatch intervals are a little longer than site unloading times. The risk of excessive truckmixer idle time on site is then considerably lessened without adding much to crew idle times.

In relation to objective 1, there is little doubt that for pours larger than about 12 deliveries, relatively low average *%TM* values of less than 140 might be reliably obtained, with little or no extra *%W* penalty, as long as the correct size of circulating fleet is also chosen. This is not necessarily an easy choice, however, because it depends on making quite accurate estimates of mean journey times and mean unloading times on site. The consequence of wrongly choosing could be severe.

System behaviour is such that a serial dispatch policy for a larger pour is likely to lead to a much greater range of possible outcomes than if circulating dispatch is chosen for the same pour and the correct size of delivery fleet is deployed. Circulating dispatch, therefore, potentially puts the plant and site managers more in control of the *(%W, %TM)* productivity to be achieved.

It is tentatively postulated, therefore, that circulating dispatch should be first considered as the default option for large pours. Further study would probably confirm this postulation, but more importantly, an understanding must first be gained, via a specific study, of the ability of plant schedulers to reliably predict the optimum size of their circulating fleet.

For pours smaller than 12 deliveries it matters little whether serial or circulating dispatch is chosen, but it remains the case that the correct fleet size must be chosen for circulating dispatch.

Data availability statement

Data analysed and generated during this study are included in the published paper.

Notes on contributors

Ir Prof 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 Department of Engineering, Lancaster University, UK for 17 years, as Head of the Department for the last six 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 what is 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 other topics, includes the benchmarking of concrete placing in the UK, West Germany, and Hong Kong, and 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.

Dr Francis Siu is currently an Assistant Professor of Construction and Real Estate Management in the Department of Building and Real Estate at The Hong Kong Polytechnic University. Dr Siu received his Bachelor of Engineering (2009) and his Master of Philosophy (2011) from the Department of Civil and Structural Engineering at The Hong Kong Polytechnic University. In 2015, he received his Doctor of Philosophy from the Department of Civil and Environmental Engineering at the University of Alberta, Canada. Dr Siu is an engineer, educator, and researcher by profession. Before returning to his alma mater, The Hong Kong Polytechnic University, as a faculty member, he worked as an engineer and consultant in construction companies in Canada, an instructor in the Department of Civil and Environmental Engineering at the University of Alberta, Canada, and postdoctoral scholar to build and supervise research teams in the Department of Civil and Environmental Engineering at the University of Alberta, Canada. Dr Siu's teaching focuses on general project management, construction process simulation, building measurement, cost estimation, tender documentation, and contract administration. His research focuses on the development and application of innovative construction methods and technologies in the fields of project planning, control, and visualisation. His service focuses on the provision of community service to professional bodies and the Hong Kong SAR Government. He also provides editorial and board member service for reputable construction-related journals. Building upon the industrial experience he gained through research collaboration with construction companies in Hong Kong and Canada, Dr Siu continues to advance his knowledge of the practical construction of buildings, infrastructure, and industrial facilities.

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