A NON-DETERMINISTIC INVESTIGATION OF THE CONCRETE PLACING SYSTEM

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ABSTRACT

Many areas of the construction industry rely heavily upon cyclical processes, some of which do not always deliver a satisfactory level of performance. One such area is the system involved in concrete placing operations. A deterministic analysis of these processes may not allow for the random distribution of system actions, resulting in unrealistic system attributes. The process of concrete batching, transport and finally placement is subject to interruption, irregularity and fluctuation and can be treated as a stochastic system. To enable contractors to deliver the highest quality of service it is fundamental that these uncertainties are managed as best as possible. Accordingly, this paper follows the flow and transfer of the concrete placing process and "lean" techniques can be applied in order to investigate the process efficiency.

For this study, examples are presented using data gathered over a two-year period from a major civil engineering project in the North-West of England. The data consists of the relevant times from over seventy concrete pours. The majority of concrete operations observed involved concrete being pumped into formwork, which was seen to be a complex queueing system.

KEYWORDS

Concreting operations, queueing systems, stochastic systems, concreting productivity, construction simulation

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INTRODUCTION

Many areas of the construction industry rely heavily upon cyclical processes, some of which do not always deliver a satisfactory level of performance. One such area is the process involved in concrete placing operations. In the construction industry concrete has been used, as a material, for many years now and while there is no shortage of research into its properties very little has been carried out concerning the delivery process. Smith (1998, 1999) modelled the supply and delivery process using discrete-event simulation and showed that there are many inefficiencies involved in the operation. It is these inefficiencies that must be analysed and removed in order to develop a satisfactory solution to the problem that is no doubt costing the construction industry millions in lost revenue each year.

Due to the nature of concrete batching, transport and finally placement many interruptions, irregularities and fluctuations are encountered for which there can be very little control. The random features of concrete operations show that they can be treated as stochastic systems. Therefore they can be treated as a queueing system that allows them to be analysed by a multitude of different techniques such as simulation, queueing theory, regression analysis and petri-net analysis.

Later in this paper examples shall be presented to enable the reader to get a closer feel for the time losses involved in a real concrete operation.

OBJECTIVES

The main objectives of these works are:

- To investigate and provide a better understanding of cyclic construction processes with particular reference to concreting operations
- To study live construction projects to gain data from these cyclic processes
- To examine methods to assist in the planning and estimation of cyclic construction processes
- To examine systems which enable construction engineering organisations to better manage cyclic construction processes, in terms of the efficiency and effectiveness of resources
- To provide systems which ultimately minimise the costs, in financial, material and human effort contexts, and maximise the productivity of concrete placing operations.

CAN THE LEAN CONSTRUCTION PHILOSPHY BE APPLIED TO THE CONCRETE PLACING PROCESS?

Koskela (1992) defined the basis for the lean construction philosophy by questioning the validity of the conventional approach to construction planning. Rather than viewing construction as a series of conversion, i.e. value-adding activities, construction should be modelled as a series of flow processes that are both waste and value-adding.

Can the concrete placing process be modelled on this basis? The conventional approach would be to plan a concreting activity based simply on the volume of concrete and the rate at which it can be pumped into the form, i.e. a simple input of raw resources (concrete, plant, labour) into an output of a something the customer requires – a concrete structure. The concrete placing process, however, potentially involves far more waste than this implies. Koskela (1992) defined a general model for the lean construction philosophy that involves the flow processes of moving, waiting and inspection; and the value-adding processing activities. This general model is ideal for the concrete placing process as it acknowledges the potentially wasteful flow processes for concrete delivery, truck-mixer queuing, concrete pump idleness, inspection etc. Only the batching and pumping activities can be considered value-adding.

In attempting to model the concrete placing process on this basis, we will treat it as a single server queuing system (see Figure 1). No account has yet been made of the batching process, which can be considered a system in its own right.

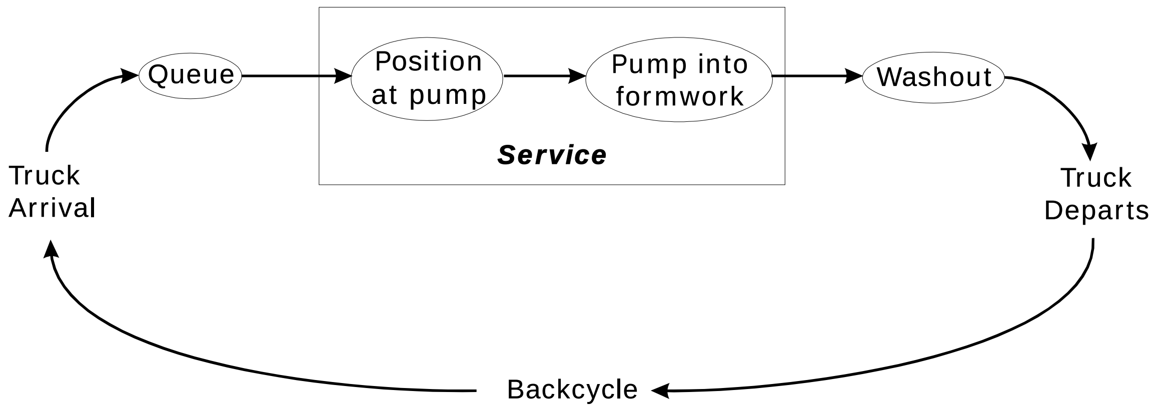

Figure 1 Schematic diagram of a general Concrete Placing Cycle

A queuing system consists of both customers and servers. For each server, customers will queue until they are served and then leave. In the case of the concrete placing process as concrete truckmixers arrive they will join the "service" (if there are no other truckmixers in the queue to be served) or join the back of the queue of waiting truckmixers. Service requires the truckmixer manoeuvring into position then discharging the concrete into the hopper of the pump, which then pumps the concrete into the required formwork. This operation is common to thousands of construction sites throughout the world. When the truckmixer has been served it will then join the backcycle until they rejoin the system – again queuing if the server is busy. In an ideal system the rate at which trucks arrive, position and have their concrete pumped would be constant. Therefore, it would be possible to estimate deterministically the time between arrivals (the interarrival time) of the trucks in order that no queuing, and thus under-utilisation, of trucks occurred. The non value-adding activity of queuing could be potentially eliminated.

A real system, however, is stochastic and the events that occur within the system (e.g. the interarrival times, pump start times) take place at irregular intervals. This point has been mentioned previously but it is one that is fundamental to the concrete placing process. Queuing of trucks can be expected, as it is unlikely that the interarrival time will be both regular and at such a rate that trucks arrive just when the previous one departs. If trucks arrive late, there will be a lengthening of the process, with plant (in particular the concrete pump) and labour becoming inactive. The rates at which trucks are used are also dependent on the speed at which they are positioned and the concrete is pumped.

There are other alternative systems available to the construction industry, for example placing concrete using a crane and bucket or by using a wheelbarrow. The later is very labour intensive and dated, however, the crane and bucket method has previously been researched (Tommelein, 1997).

By modelling the flow processes within concrete placing we can attempt to minimise their variability. In order to do so, however, we must attempt to identify the factors that cause this variability.

IDENTIFYING UNCERTAINTIES IN THE CONCRETE PLACING CYCLE

In the majority of concrete pours it is possible to determine a number of factors that are detrimental to the quality of the concrete placing process. Establishing these factors, which are the cause of the stochastic nature of the system, may well allow a reduction in the variability of concrete operations and so reduce wastage. Crombie (1999) set about determining these factors and these can be seen in Table 1 below. The factors have been evenly split into two groups, technical and managerial factors, which show that equal emphasis should be placed on good managerial practice. Crombie (1999) concluded that as many as 44 factors would need to be managed, as best as possible, in order to achieve a satisfactory CPC.

Table 1 Factors that can affect the efficiency of a concrete operation. (Crombie, 1999)

TECHNICAL FACTORS	MANAGERIAL FACTORS
1. GRADIENT OF THE SITE	22. PLANNING
2. SITE CONGESTION	23. PROGRAMME
3. OTHER SITE ACTIVITIES	24. RATE OF PROGRESS REQUIRED
4. ACCESS CONDITIONS	25. TIME RESTRICTIONS
5. SITE LOCATION	26. COMPANY STRUCTURE
6. PLACING METHOD	27. COMPETENCY OF MANAGEMENT TEAM
7. LOCATION OF SUPPLIER	28. ENGINEER'S EXPERIENCE AND INTUITION
8. POUR SIZE	29. MOTIVATION OF ENGINEER
9. POUR LOCATION	30. ENGINEER’S MANAGEMENT SKILLS
10. POUR SHAPE	31. SKILL OF PLACING TEAM
11. HEIGHT OF POUR	32. EXPERIENCE OF SITE TEAM
12. AGE OF TRUCKS	33. MATURITY OF PERSONNEL
13. SUITABILITY OF PLANT FOR JOB	34. MOTIVATION OF PLACING TEAM
14. FORMWORK	35. JOINER AND STEEL-FIXER EFFICIENCY
15. SEQUENCE OF POURS	36. MAINTENANCE OF PLANT
16. ACCURACY OF TAKE-OFF	37. TIMELY SUPPLY OF CONCRETE
17. TESTING	38. SUPPLY OF MATERIAL
18. CONCRETE SPECIFICATIONS	39. QUALITY OF PLANT
19. OUT OF SPECIFICATION DELIVERIES	40. SUPPLIER’S OTHER CONTRACTS
20. SPILLAGE	41. RESOURCES OF SUPPLIER
21. VANDALISM	42. LABOUR REQUIREMENTS
	43. ACCIDENTS
	44. WEATHER CONDITIONS

By considering these factors in the context of the main parts of the concrete placing process (Figure 1) we may begin to understand how variabilities can be reduced:

Truck Arrival

When the truck arrives at site there will be a number of factors that will prohibit it getting to the pump without delay. Once at the site it is extremely important that the driver knows exactly where to go to and the best route to get there. This is a problem early on in projects, or if suppliers are being used for the first time, so the contractor may allow for this and reduce the expected pumped volume of concrete for the first few hours until everyone is familiar with the site. The site itself contributes to many delays, whether it is because of the layout or the congestion of the working area.

Queue

Ideally, queueing of truckmixers is to be avoided, but unfortunately this is not always possible. If trucks have to queue then time delays occur and hence there is wastage of resources. To avoid this it could be appropriate to use the much talked about 'Just-In-Time' methodology. This suggests that the delivery of a material to its final installation location on a construction site will happen without delay due to storage in a lay down or staging area. In this scenario the 'lay down' or 'storage area' can be equated with the queue.

In practice this approach would require a truckmixer to arrive on site at the pump at the exact moment the previous truckmixer leaves. Unfortunately it has to be accepted that even the slightest amount of variability in truckmixer travel speeds would make such a situation very difficult to achieve. In many cases a short queue of truckmixers will ensure full utilisation of the concrete pump. Thus the practitioner is faced with the more pragmatic task of minimising the under-utilisation caused by truckmixer queues and pump idle time rather than trying to eliminate it.

Service

This is the stage that sees the concrete being pumped into the required formwork. Once a space has arisen at the pump the first truck in the queue will manoeuvre itself into position at the hopper and then pumping will commence. The pumping stage's efficiency depends on many factors none more so than the skill of the placing team. A good, experienced placing team has the potential to save many valuable seconds or even minutes. The service stage is a large part of the cycle time – and as well as the pumping process, it is necessary to add time for routine tests to the concrete. In a well run operation this should not interfere greatly with the concrete pumping. When all the concrete has been discharged the truck will be washed out and leave the site so that the next truck in the queue can be moved into position.

The time for a truck to move into position and ready to pump may only be of the order of a few minutes – but a simple deterministic calculation shows that a large concrete pour of say, 60 truck loads and an average position time of 2 minutes, produces 2 hours of non value-adding activities. This is a large wastage for one day's deliveries. The situation can be improved by having two trucks in position at the same time, as depicted in Figure 2. This would cut down the position time and save valuable time throughout the length of the pour – but of course does not increase the utilisation of the truckmixer time. Because of the positioning of the trucks one truck will be able to manoeuvre into position while the other is discharging its concrete. This same concept has been used to good effect in another construction process, earthmoving, where an empty dumptruck is positioned next to one being loaded. When the excavator has filled the first truck, the second can be serviced without a break in the excavator's operations.

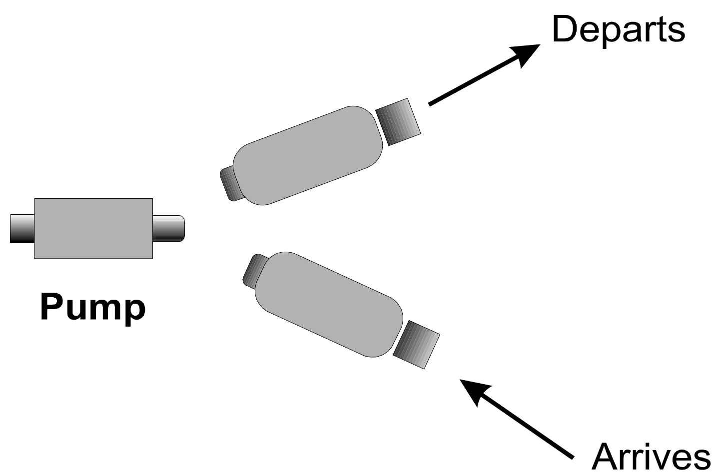

Figure 2 An example of truck positioning at the hopper of the pump, which may reduce the overall pour time

Backcycle

When the truck leaves the site it enters the backcycle. In many cases the truck will be required to use public roads, which increases the chances of congestion and further delays. The time taken for the backcycle is as important as the time to get the concrete to site because close control is required if the supplier and contractor are going to able to schedule deliveries effectively. For this reason many contractors prefer to have concrete delivered at off-peak times so reducing the possibility of increased waste.

Once the truck arrives at the batching plant it will enter another queueing system in order to receive the next batch of concrete.

DATA COLLECTION AND ANALYSIS

The next stage in order to investigate and assess the wastage that occurs in the concrete placing cycle through its variability, is to collect data from real construction projects. This data can be used to analyse a model of the system.

There are numerous tools by which a model of the concrete placing cycle can be analysed. The most relevant of these are now briefly discussed:

i. *Queuing Theory*. An operations research technique used in many applications. Its application to construction has been extensively researched by Carmichael (e.g. 1986, 1987) who applied the theory to earthmoving and mining operations.

ii. *Simulation*. A simulation model involves some element of dynamism, if only because it models a process rather than an object (Fellows et al, 1999). This makes simulation ideal for concreting operations. By synthesising input data based on the probability distributions of actual operations, each step of an operation can be recreated. A computer can recreate each step very quickly thus allowing the simulation of lengthy, real operations.

Simulation applied to construction operations is not new. Much work has been done in this area since the seventies, the majority of research being carried out in the United States at institutions such as the Construction Institute at Stanford University and at The University of Illinois.

In the seventies Halpin developed CYCLONE which was later extended at Stanford University (Halpin 1977). This program has instigated most of the work in simulation techniques in the last two decades, with most of the research in the United States using CYCLONE or one of its many offsprings. These modifications have included INSIGHT (Kalk and Douglas 1980; Paulson et al. 1983 and 1985). Bernold developed a version called UM-CYCLONE (University of Michigan - CYCLONE) as part of his PhD research and used the program to aid in earthworks quantities and resource allocations (Bernold 1986) as an alternative to the mass haul and linear programming.

In the past decade a very prolific researcher in computer simulation applications in the construction industry is Simaan AbouRizk at the University of Alberta in Edmonton. Starting with research with Halpin at Purdue University, variance reduction techniques were developed for simulation programs (mainly CYCLONE and MicroCYCLONE) to reduce the number of simulation runs required (and hence run time) without sacrificing the level of confidence of the output (AbouRizk et al. 1990). This of course is not as necessary any more as the speed of computer simulation programs has increased so that computer simulation run time is no longer a limiting factor in the development of simulation models.

iii. *Petri Net Theory*. This theory allows a system to be modelled by a Petri net, a mathematical representation of the system (Wakefield and Sears, 1997). Analysis of the Petri net can then, hopefully, reveal important information about the structure and dynamic behaviour of the modelled system. This information can then be used to evaluate the modelled system and suggest improvements or changes.

iv. *Neural Networks*. Artificial neural networks are computational devices. Most researchers and developers at this time simulate their neural networks using software simulation. A neural network is a highly interconnected network of many simple processors each of which maintains only one piece of dynamic information and is capable of only a few simple computations. No previous work has been found exploiting the uses of neural networks in concrete operations so further research is being carried out in this area.

v. *Regression Analysis*. This is a statistical tool that provides equations for outputs derived from real operation data. These equations can then be used to deterministically analyse further operations. Regression analysis provides the chance to analyse the variables in pairs – one dependent and one independent. Fellows et al, state that regression analysis establish only any relationship between the realised values of the variables which occur; they do not establish causality. This may have to be taken into account at a later date.

INVESTIGATING THE CONCRETE PLACING CYCLE

We have seen that the concrete placing cycle is subject to a number of factors that cause random fluctuations – these in turn cause wastage within this process.

To conclude this paper we shall look at two examples of investigations that have been carried out using real data collected in the UK.

Wastage by inspection

Table 2 shows a small amount of data taken from a major civil engineering project in the North-West of England. The project involved the construction of a motorway viaduct and widening and involved pours ranging, for the whole project, from $2m^3$ to $1200m^3$ of concrete. The table shows the pour records for just one operation.

In this operation the total amount of concrete ordered was 126 m^3. The concrete was called up from the (site) batcher at 07:00hrs with the first concrete placed at 07:14hrs. All of the concrete was ordered from the same batching plant and was pumped by the same pump. Three truckmixers were used.

Table 2 Pour record sheet taken from a real construction project

	Time (hh:mm)				Calculated Times (hh:mm)					
Truck	Batch	Arrive	Start	Complete	Inter - arrival Time	Truck Wait Time	Truck Position Time	Load Pump Time	Pump Inactive Time	Truck Cycle Time
1	07:01	07:10	07:14	07:25						
2	06:57	07:25	07:28	07:35	00:15	00:00	00:03	00:07	00:05	
3	07:17	07:40	07:43	07:50	00:15	Truck Late	00:08	00:07	00:05	
1	07:45	07:55	07:58	08:05	00:15	Truck Late	00:08	00:07	00:10	00:44
2	08:05	08:15	08:18	08:25	00:20	Truck Late	00:13	00:07	00:05	01:08
3	08:21	08:30	08:33	08:40	00:15	Truck Late	00:08	00:07	00:05	01:04
1	08:37	08:45	08:48	08:55	00:15	Truck Late	00:08	00:07	00:00	00:52
2	08:47	08:55	08:58	09:10	00:10	00:00	00:03	00:12	Truck on-time	00:42
3	08:55	09:05	09:11	09:20	00:10	00:05	00:01	00:09	00:05	00:34
1	09:13	09:25	09:28	09:35	00:20	Truck Late	00:08	00:07	00:15	00:36
2	09:33	09:50	09:53	10:00	00:25	Truck Late	00:18	00:07	00:05	00:46
3	09:53	10:05	10:07	10:10	00:15	Truck Late	00:07	00:03	00:05	00:58
1	10:02	10:15	10:18	10:25	00:10	Truck Late	00:08	00:07	00:05	00:49
2	10:07	10:30	10:33	10:45	00:15	Truck Late	00:08	00:12	00:00	00:34
3	10:18	10:45	10:48	10:55	00:15	00:00	00:03	00:07	00:05	00:25
1	10:36	11:00	11:03	11:10	00:15	Truck Late	00:08	00:07	00:00	00:34
2	11:00	11:10	11:13	11:20	00:10	00:00	00:03	00:07	00:05	00:53
3	10:59	11:25	11:28	11:45	00:15	Truck Late	00:08	00:17	Truck on-time	00:41
1	11:25	11:30	11:45	11:50	00:05	00:15	00:00	00:05	Truck on-time	00:49
2	11:34	11:45	11:53	12:05	00:15	00:05	00:03	00:12	Truck on-time	00:34
3	12:00	12:10	12:12	12:35	00:25	Truck Late	00:07	00:23		01:01
			Overall operation time=	**05:34**		**00:25**	**02:13**	**02:57**	**01:15**	**13:44**

As can be seen by inspection of this data there are three areas of wastage within this operation:

- Firstly, although many of the concrete deliveries arrived late, some arrived early thus involving a wait and an under-utilisation of the truckmixer. The total amount of wait time was 25 minutes – comparing this with the total amount of time the trucks were in use for (i.e. 13 hours and 44 minutes) gives a non-value adding wastage of 3%. This is probably well within what could be expected.
- The second area of wastage occurs because many of the deliveries were late, i.e. after the previous truck had departed. We can see that the total time that the pump was inactive on this operation was 1 hour and 15 minutes and this time it is compared to the time from the first delivery to the last, in this case 5 hours and 25 minutes. The wastage here is a very high 23% – that is nearly a quarter of the pump's time was non-value adding.
- Finally we see that 2 hours and 13 minutes of truckmixer time was spent positioning at the pump. This equates to 16% of total truckmixer time. Whilst we have see that truck positioning is an integral part of the concrete placing cycle it can be considered non-value adding – in Figure 2 we saw how the impact of truck positioning time can be minimised in a concrete placing operation.

The effect of varying Interarrival and Pumping times

It has been established that the concrete placing cycle consists of a number of time components: this paper has introduced the truckmixer interarrival and position times and the pump time. In the example given above we can see that the utilisation of the pump is low (77%) whilst that of the truckmixers is quite high (97%). We can attribute this to the truckmixers generally arriving late at the concrete pump and to improve the pump utilisation in this operation, truckmixer interarrival times could have been reduced. At some point, however, the reduced interarrival times would cause the truckmixers to queue thus increasing their under-utilisation.

We can investigate this situation, not by varying the interarrival times on a real pour but by experimenting with a simulation model. Using a discrete-event simulation model programmed into Microsoft Excel, the interarrival time for a theoretical operation was modelled and varied, using a gamma probability distribution, from a mean of 200 to 1500 seconds (see Smith, 1998). The position time was kept constant at 276 seconds and the pump time maintained at 482 seconds (seen to be typical times from observed operations). 46 truckmixers were modelled, delivering a total of 276m^3 of concrete. Figure 3 shows the result of this experiment.

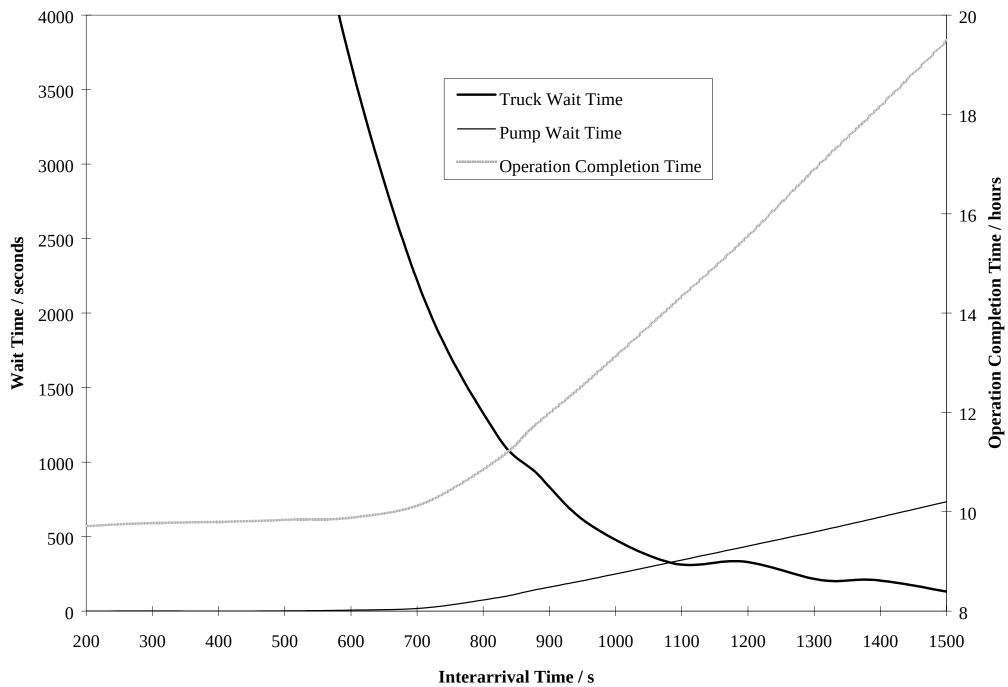

Figure 3   Results of an experiment in varying the interarrival time

From Figure 3 it can be seen that the minimum operation completion time is around 9.9 hours. However, as this time is mainly dependent on the rate at which the concrete pump actually provides concrete to the formwork, it can be achieved only if the concrete pump is not idle at any time. Unfortunately, as this is a stochastic situation, to ensure the pump is not idle, the interarrival time needs to be very low (<700 seconds) to ensure a constant supply of concrete. The chart indicates that this results in excessive truck wait times: more than 1.5 hours on average per truck.

Alternatively, if the waiting of trucks is to be kept to a minimum, this can be achieved by allowing some idle time of the pump. This, however, has the unfortunate result of nearly doubling the operation completion time with a consequent increase in cost of plant and labour.

For the operation modelled the optimum interarrival time must be the time at which both the truck and the pump wait times are minimised – approximately 1090 seconds (18 minutes 10 seconds). By this method the ideal operating conditions can be estimated for any concrete placing operation that provide the minimum of wastage of resources.

Similarly it is possible to carry out an experiment that changes the pump times to see the effect that this has on the operation. Again, if position and interarrival times are kept constant the ideal pumping time that minimises wastage can be estimated. In this situation, however, there is less scope for actually using this ideal pump time as the rate of concrete placing depends on other factors – such as the shape of the formwork.

On the basis described above, the optimum interarrival times can be established for a series of pump times. Through a series of experiments, 12 optimum interarrival times were determined for a range of pump times (50 – 900s), the results of which can be seen in Figure

4. The optimum operating conditions provide a straight line (best fit provided) that can be compared to the deterministic situation derived by assuming that all times are constant and not stochastic. The deterministic line is a result of the fact that if all times were constant, the interarrival time needs to be the sum of the position time plus the pump time for zero waiting. As can be seen for any pump time the interarrival time is greater than may be expected from the deterministic situation: if an operation used the deterministically derived interarrival time (i.e. shorter than ideal) then in a real, stochastic situation excessive truck waiting would occur as demonstrated in Figure 3.

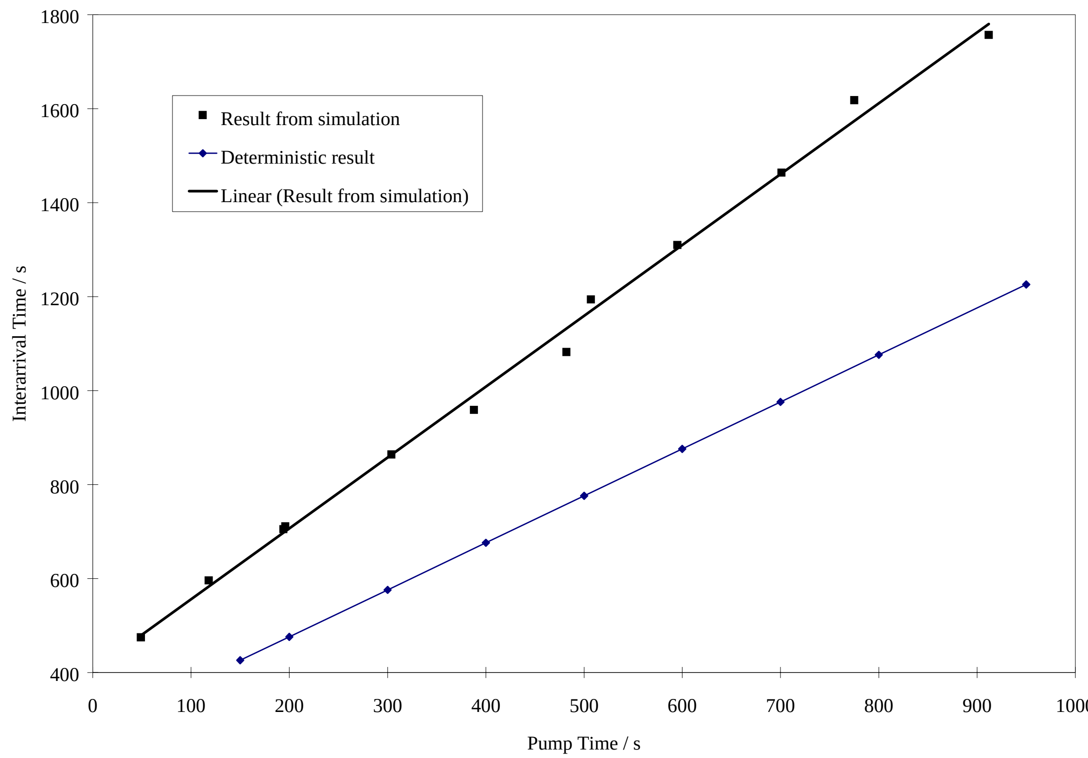

Figure 4   Optimal operating conditions determined by simulation experimentation

CONCLUSIONS

In this paper we have studied the cyclic construction process of concrete *batching, delivery, pumping and return*. It has been shown that considerable wastage of resources in this operation can occur through two main reasons:

- The cycle has a component, truck-positioning time, that can be considered non-value adding. That is when a truckmixer is manoeuvring itself from the queue into position behind the concrete pump, the pump in inactive and no concrete is being placed into the formwork. All plant and labour during this time are being wasted. Whilst the truck-positioning time cannot be eliminated it is important that its effect on the operation be understood – and this effect can be minimised by active management of the pumping operation: by having one truck in position whilst another is discharging the pump can smoothly transfer between the two trucks (see Figure 2)

- In a real situation the concrete placing cycle is stochastic. The variability of such a system, if ignored, can result in poor estimates of concrete placing output. It has been shown that such a system can be modelled in a non-deterministic manner and analysed via a number of operations research technique. Perhaps the easiest of these techniques to implement is *simulation* and a variation, discrete-event simulation, has been used to carry out experiments on the system. It has been shown that the operating conditions for any concrete pour that produce the minimum of wastage of resources can be estimated using this method and, further, that these conditions are different than those estimated by assuming the system is deterministic. If deterministic results were used in a real situation then wastage of resources may occur.

REFERENCES

AbouRizk, S.M.; A.A.Gonzalez-Quevedo and D.W.Halpin (1990) Application of Variance Reduction Techniques in Construction Simulation. *Microcomputers in Civil Engineering, 5.* 299-306.

Bernold, L.E. (1986) Low level artificial intelligence and computer simulation to plan and control earthmoving operations. *Earthmoving and Heavy Equipment, Proceedings of the Conference, ASCE.* 156-165.

Carmichael, D.G. (1986). Erlang loading Models in Earthmoving. *Civil Engineering Systems,* **3** 118-124.

Carmichael, D.G. (1987). *Engineering Queues in Construction and Mining.* Ellis Horwood. Chichester

Crombie, R. (1999). Efficiency, Quality and Wastage in Concrete Operations. *B Eng Honours Thesis*. The University of Edinburgh.

Fellows, R.; Liu, A. (1999). *Research Methods for Construction*. Blackwell Science.

Halpin, D. W. (1977) CYCLONE: Method for modelling of job site processes. *Journal of the Construction Division, ASCE. 103,* 489-499.

Kalk, A and S. Douglas (1980) Insight: Interactive simulation of construction operations using graphical techniques. *Technical Report no. 238.* Construction Institute, Stanford University, Stanford, California.

Koskela, L. (1992) *Application of the New Production Philosophy to Construction*, Technical Report 72, CIFE, Stanford University, Stanford, CA, September, 75 pp.

Paulson B.C.; S.A.Douglas; A.Kalk; A.Touran and G.A.Victor. (1983) Simulation and Analysis of Construction Operations. *Journal of Technical Topics in Civil Engineering, ASCE 109 (2).* 89-104.

Paulson B.C.; W.T.Chan and C.C.L.Koo (1985) Simulating Construction Operations by Microcomputer. *Construction Research Applied to Practice, ASCE.* 35-49.

Smith, S. D. (1998). Concrete placing analysis using discrete-event simulation, *Proceedings of the Institute of Civil Engineers*, Structures and Buildings, 128(4), 351-358.

Smith, S. D. (1999). Modelling and Experimentation of the Concrete Supply and Delivery Process, *Civil Engineering and Environmental Systems*, Vol 16, 93-114.

Tommelein, I.D. (1997) Discrete-Event Simulation of Lean Construction Processes, *Proc. 5th Ann. Conf. Intl. Group for lean Constr.*, IGLC-5, 16-17 July at Griffith Univ. – Gold Coast Campus, Queensland, Australia, 121-135.

Tommelein, I.D.; Li, A. E. I. (1997) Just-In-Time Concrete delivery: Mapping Alternatives for Vertical Supply Chain Integration, *Proc. 7th Ann. Conf. Intl. Group for lean Constr.*, IGLC-7, 26-28 July at University of California, Berkeley, CA, USA. 97-108.

Wakefield, R.R. and Sears, G.A. (1997) Petri Nets for Simulation and Modeling of Construction Systems. *Journal of Construction Engineering and Management*, 123 (2), 105-112.