Investigation, modelling and planning of stochastic concrete placing operations

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This thesis is original and has been written and compiled solely by Paul G. Dunlop under the supervision of Dr Simon D. Smith

Where other sources are quoted, full references are given.
Abstract

The concrete delivery and pumping process is a stochastic system. If analysed deterministically there is the danger that the negative effects of the random distribution of events are not taken into account, leading to poor estimates of production and cost. By representing the system as a random process the construction engineer can firstly achieve improved estimates of the overall productivity and thus schedule deliveries better, and secondly, determine the effect of non-anticipated events such as excessive delivery or pour times.

This research is centred on studies of actual construction projects, which are used to study cyclic processes in general, and concreting placing operations in particular. The dataset used was gathered from over 345 concrete pours, and represents one of the largest of its type. This dataset was used as a basis for the modelling of concreting operations.

These models were developed and analysed using a number of techniques, notably lean construction principles, multiple regression analysis and Monte Carlo simulation.

The outcome of this research is a better understanding of how cyclic construction processes are managed and planned at a grass roots level. Firstly, by applying lean construction theories to concrete operations in the UK it was found that many are being carried out with an unacceptable amount of wasteful activities. By understanding lean construction principles some headway can be made to ensure that in future this waste is not only understood but also eliminated. Secondly, a multiple regression analysis was carried out with excellent results. Not only was it possible to identify those factors that most effect the performance of concrete placing, but also a model was developed that allows planners and engineers alike to accurately predict key responses such as pour duration and expected productivity. Finally, a simulation analysis was carried out which highlighted how the overall process reacted to changes in key times such as pump, interarrival and waiting time on site. By knowing how the process behaves and reacts to change it is possible to calculate the optimum operating conditions.
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Chapter 1

Introduction

With an increasingly competitive global market the UK construction industry is realising that in order to be competitive, a marked increase in efficiency will have to be achieved in all areas. This research project looks at the concrete delivery and placement process. This chapter serves an introduction to this process and explains the problems that need to be addressed.
Chapter 1 Introduction

1.1 Background

In the UK, and indeed the rest of the world, concrete is a very valuable building material and one that is used on the majority of construction projects. The UK 'ready-mixed' concrete industry is very large: Figure 1.1 shows that between 1991 and 2003 it supplied an average of 22.3 million cubic metres of fresh concrete per year (DTI, 2004). The cost to the contractors who use this concrete is therefore, depending on which estimate one uses for material price, between £1.1 billion and £1.6 billion per annum. This is just the material cost, which is generally considered to be approximately 40% of total costs. It follows on that the total cost of in-situ concreting operations to UK contractors could be as high as £4 billion per annum.

As a topic for research, the placement of fresh concrete on UK construction sites can in no way be considered insignificant: resource 'waste' of just 1% would amount to some £40m per year – experience would suggest that construction inefficiencies are actually much higher than this.

![Figure 1.1: Ready Mixed Concrete Deliveries in the UK – 1991 – 2003 (Source DTI, 2004)](image-url)
Latham (1994) in his review of the UK construction industry suggested that productivity improvements in the UK of up to 30% were necessary to face the challenges of the next millennium. Egan (1998) added to this, building on Latham's earlier work, suggesting that productivity be increased by 10% per year. At the time of Egan's report productivity was increasing by an average of 5% per year with the best projects demonstrating increases of up to 15%. These figures reflect the current improvements in the UK construction industry today, though there is still room for further improvements.

Against this background, the research project for which this PhD and thesis are part of has been set. Section 2 of this introduction will briefly introduce this project, including its aims and objectives, which are those that have been applied to the PhD project. Section 3 will discuss further what concreting operations actually are, with emphasis on the two components of batching plant and construction site. Section 4 will complete this introductory chapter by broadly considering the ways in which concrete operations can be investigated.

1.2 Research Project: *Stochastic planning of concrete placing operations*

The background above has indicated the nature of the concrete business (and the construction industry). What will be seen later in this chapter is that the concrete placing operation, so common to so many construction projects, is actually a stochastic process which cannot be investigated by conventional, deterministic techniques. In 1999 the Engineering & Physical Sciences Research Council awarded a research grant to the then School of Civil & Environmental Engineering (Principal Investigator Dr Simon Smith). This grant, for the sum of £55,590, allowed this problem to be investigated by means of studying construction projects and developing appropriate models, via a PhD Project Studentship. The Aims and Objectives of this research project are therefore the same aims and objectives which apply to this thesis and can be summarised below:

1. To investigate and provide a better understanding of cyclic construction processes with particular reference to concreting operations;

2. To study live construction projects to gain data of cyclic processes;

3. To examine methods to assist in the planning and estimation of cyclic construction processes;
4. To examine systems which enable construction engineering organisations to better manage cyclic construction processes, in terms of the efficiency and effectiveness of resources; and

5. To provide systems which ultimately minimise the costs, in financial, material and human effort contexts, and maximise the productivity of concrete placing operations

These five aims and objectives are those for which the success of both the research project itself and the thesis will be judged.

1.3 Concrete Operations Explained

It can be seen that Figure 1.2 consists of two distinct cycles: the batching plant and the construction site. Both of these are cyclic and can be treated as single server queuing systems. A queuing system is characterised by three components: arrival process, service mechanism, and queue discipline. Specifying the *arrival process* for a queuing system consists of describing how customers arrive to the system. The *service mechanism* for a queuing system is articulated by specifying the number of servers, whether each server has its own queue or there is one queue feeding all servers, and the probability distribution of customers’ service times. For the purpose of this study it has been assumed that only one server is available. The *queue discipline* of a queuing system refers to the rule that a server uses to choose the next customer from the queue (if any) when the server completes the service of the current customer (Law and Kelton 1991). In the case of concrete operations customers are normally served in a first-in, first-out manner (FIFO) due to the nature of concrete’s shelf life.
1.3.1 The Batching Plant
The concrete supplier plays a very important role in concrete operations and should be very carefully chosen by the site operator. Whilst the site operator will only be dealing with his project the concrete supplier will quite often be acting as supplier to many construction sites with a fixed or limited amount of resources. This requires precarious juggling of plant and resources to ensure the safe and reliable delivery of concrete.

When the site operator orders concrete it will generally be done as a bulk order at the beginning of the project, e.g. 8,000 m³ of one type of concrete and 6,500 m³ of another. This allows the supplier to ensure that he has all necessary raw materials close at hand so that when the site operator submits the, usually weekly, order specifying how much concrete required to be delivered per day the concrete will be ready to be dispatched. It is usual practice in the UK for the concrete supplier to transport the concrete to the required location...
construction sites using their own truck mixers, though occasionally the contractor may use their own plant. Quite often the number of truck mixers used on each pour will be set by the supplier once they calculates how many are required for other jobs. In most cases the site operator would very much like to have the opportunity of dictating how many trucks are to be used on each day, however it is very rare for this to take place. One step that has been taken in order to achieve this authority has been to form alliances between customers and suppliers.

When the concrete is ordered the raw materials are selected and mixed to the customers required specifications. An available truck mixer will then move into place and have the concrete discharged into its drum. The truck is then free to leave the batching plant and travel to its destination. When a batching plant is being fully utilised there will be many trucks arriving and departing the site and in many cases this will lead to queues forming at the point were concrete is discharged into the drums. This slows down supply of the concrete to the customer and has a knock on effect throughout the system – but also results in an under-utilisation of the supplier's resources.

1.3.2 The Construction Site
In this study the construction site cycle will form the heart of the analysis of concrete operations. This is in part due to the nature the data were collected, however, it is mainly due to the fact that events on construction sites are still seen as the most important to the success of the overall project. For example, during a concrete pour very little thought or consideration is given to what happens to the concrete before it reaches site and indeed contractors may say rightly so. However, when problems start to crop up during pours it may make life very difficult if prior consideration is not given to the batching process and the route the concrete is being transported over. All to often the phrase, “as long as it arrives” was heard on construction sites with very little regard to idleness.

The concrete is ordered and the site operator will have given the concrete supplier a pour start time, a description of the type of pour therefore telling the supplier how quickly he would like the concrete delivered (fast regular delivery for base pours and slower controlled delivery for wall and column structures). After this it is more often than not left for the
supplier to use his own conception and decide on the speed of delivery etc. For example consider a 36 m³ concrete pour with the supplier having 6 trucks available each with a capacity of 6 m³ so he may decide to send each truck once or to deploy some of the trucks to other jobs and increase the number of visits some trucks make to site.

When the truck mixers arrive on site they will have the task of finding the appropriate area of the site where the concrete is to be discharged. On arriving at the designated area the truck will position itself at the hopper of the concrete pump (if there are no other truck mixers in the queue to be served) or join the back of the queue of waiting truck mixers, see Figure 1.3. Once positioned at the hopper of the pump the concrete will then be slump tested to ascertain if it falls within the limits required by the site operator. The slump test will determine how workable the concrete is and is primarily governed by the “wetness” of the concrete. A concrete mix that is too wet and falls out with the predetermined limits will, in practise, immediately be rejected deeming the whole load worthless. Conversely if the mix is too dry water may be added to the mix in order to bring it within the workable limits (this may only be done once the site operator has given the supplier permission to do so). As and when the concrete has passed the slump test it will then be discharged into the hopper of the concrete pump, which in turn pumps it into the required formwork (see Figure 1.4), with the help of the placing team, see Figure 1.5. The concrete is then vibrated by the placing team and left to cure (see Figure 1.6). Meanwhile the truck mixer will then travel to a designated area of the site where all excess concrete is washed away before it can enter the public road network on its way to the batching plant, see Figure 1.7.
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Figure 1.3: Concrete Truck Positioning at Hopper of Pump with Waiting Truck in Queue in the background

Figure 1.4: Typical Formwork
Figure 1.5: The Placing Team Directing Concrete into Required Formwork

Figure 1.6: Placing Team Compacting Concrete
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 occurs. The non value-adding activity of queuing could be potentially eliminated. A model of such an ideal system is very simple, with attributes being calculated easily. The time taken to complete a concrete pour, assuming all trucks used to be of equal volume and that trucks are scheduled to arrive so that they do not queue, is:

\[ T = \frac{Q}{v} (t_{\text{pos}} + t_{\text{pump}}) \]  

Equation 3.1

Where \( T \) is the overall time, \( Q \) is the total quantity of concrete, \( v \) is the volume of a truck, \( t_{\text{pos}} \) is the time taken to position the truck ready to discharge concrete and \( t_{\text{pump}} \) is the time taken to pump the concrete.
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 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.

1.4 Investigating Concrete Operations

Concrete operations have been briefly introduced and outlined above and in particular problems related to the efficiency of the operations have been highlighted. In order to investigate these operations, that are so pertinent to the UK construction industry, it was firstly important to decide on a methodology to be used. The work presented uses classical problem solving techniques: firstly, to identify the problem, then propose possible solutions, test and redevelop these ideas and finally, implement and maintain a proposed method of solutions.

The main problems thought to exist in concrete operations in the UK is that presently there appears to be a very limited understanding or appreciation of the savings that can be made through better management and control of the delivery and placement of fresh concrete in the UK. Productivity studies have been carried out for many years now on individual activities in the UK construction industry, but practitioners rarely attend the conferences where such data and the conclusions drawn from them are. Part of this problem is that contractors' personnel does not possess enough statistical knowledge of the concrete supply process to be able to make informed decisions on the application of predictive models. Graham (2005) has coined this the 'Complexity Problem' and has started to develop models which remove the need for this knowledge from contractors. In the study presented in this thesis, to understand the situation as fully as possible the first step was to therefore simply observe and record real concrete operations. The observation of real concrete operations was undertaken for approximately nine months and the subsequent dataset collated is arguably one of the largest and most complete available to researchers in the UK.
In order to accurately collect the data required from the concrete operations, work-study techniques were used which required full consultation with all the site personnel involved. It was important to be open and honest with those operatives that were ultimately being watched and assessed in order to avoid conflict and unnatural working habits. This ensured that any conclusions drawn from the observations could be relied on and used in any subsequent model. Five major civil engineering projects, involving varying volumes of concrete pours, have been used in this study to various degrees and the raw data gathered from them form the basis for any model and solutions proposed in this study. These projects and the initial work undertaken are described in chapter 3.

The next stage is to develop possible solutions to the identified problems. This has been an iterative process. The first solution was a relatively simple study of philosophies that already existed within construction management. Interestingly, the chosen philosophy for further investigation – lean construction – was actually developed from the car manufacturing industry. Lean construction provides a very interesting insight into how lessons can be learnt from a very different but intrinsically linked industry. Lean thinking has already been used with very effective results within the construction industry, nevertheless, the application of its principles to a specialised construction activity such as concrete operations has rarely been attempted and many positive conclusions can be drawn from the study. Chapter 4 presents a study of lean construction and an attempt has been made to apply it to the roots of the construction industry.

Following the time spent on site observing real concrete operations it was the investigators realisation of the multitude of factors affecting productivity rates in UK construction sites that lead to the next technique to be used for investigation. Chapter 5 introduces regression analysis as the next tool to be implemented. By utilising a relatively simple mathematical procedure such as regression analysis, it was realised that many different objectives could be achieved. The first was to identify those factors that significantly influenced a response, such as productivity or pour duration. Regression analysis allows this, as the final regression model developed will only include those factors that most affect the response. By producing a regression model this covered the next two objectives: firstly, it allowed the data
collected on site to be used effectively and secondly, and more importantly, the regression model was to become the first predictive tool for concrete operations.

Although effective, it was realised that regression analysis did not allow the level of flexibility required to fully investigate the complexity of concrete operations. In chapter 6, simulation techniques were used to further investigate the problems identified. By using the experience gained from the previous approaches a simulation model was developed using a computer simulation program called @Risk (Palisade, 2004). The model was developed using the data collected on site and introduced in Chapter 3.

As with all problems, any solutions proposed have to be fully tested to ensure results obtained are reliable. In this situation, a further problem is that a simulation model is very good at providing many results and hence the user soon becomes to believe that the data obtained is accurate. The simulation model, as well as the regression model, were validated to ensure that models represent as close as possible real life situations and that any decisions made through using the models are the correct ones.
This chapter presents a review of current practices in the UK construction industry, followed by a discussion of some lessons that need to learnt before any improvements can be achieved. Also, a detailed summary of existing tools and techniques used within the construction industry for planning and estimating cyclic processes is presented.
Chapter 2 Literature Review

This chapter is essentially a review of current practices in the UK and indeed practices and research that has been used and carried out worldwide. In many ways it is an extended introduction to Chapter 1. In this chapter the scene will be set for the best approaches in order to study concrete operations effectively and indeed it was the starting point for this research project.

To begin with a brief history of concrete operations in the UK will be given along with a few comments on the likely state of the industry in the future. Concrete operations will then be looked at, including an overview of past methods and planning tools used, and research carried out in this area will be discussed.

2.1 A brief history of concrete in the UK

Concrete has been used in construction for over 2,000 years, perhaps first by the Romans in their aqueducts and roadways.

The Romans used a primitive mix for their concrete. Mortar consisted of small gravel and coarse sand mixed together with hot lime and water. To reduce shrinkage, they used horse hair, much like we use polypropylene fibres today. They even unintentionally entrained the air in the mix by adding animal blood. That process created small air bubbles in concrete, making the mix more durable.

Having established that concrete has been used in construction for many years, it cannot be forgotten that even in earlier times builders and engineers would always have had the problem of deciding what approach to use to get it to its final destination.

Nowadays, concrete is used in vast quantities for a multitude of structures - from bridges to walkways. Many of the earlier concrete roads in the UK are now being replaced by state of the art mixes of asphalt and bitumen. That being said, concrete is still one of the most used building materials in the UK, with over 1000 concrete batching plants in the UK.
2.1.1 Quality Regulations in the UK Ready Mixed Supply

With the advent of a heightened quality control within the construction industry, ready mixed concrete suppliers are now governed by the Quality Scheme for Ready Mixed Concrete (QSRMC). QSRMC was established to provide product conformity certification for ready mixed concrete supplied throughout the UK. It is a specialist body which brings together the producers of ready mixed concrete and a broad range of their customers, to set the standards for certification and for the assessment of the producers. The Scheme is governed by an independent Board which reflects the partnership between the producers and the specifiers and purchasers of concrete.

The QSRMC Quality and Product Conformity Regulations are the product conformity certification standard for ready mixed concrete. These Regulations were drawn up by an expert group of specifiers and purchasers of concrete in consultation with the ready mixed concrete suppliers and the QSRMC management. The QSRMC Regulations have been approved by the Governing Board and are enforced by the Manager of the Scheme. He is supported by an assessment team of engineers who by their qualifications, experience and training understand concrete technology and the requirements of specifiers and purchasers.

QSRMC is committed to giving a value added service to ready mixed concrete producers and to their customers by providing:

- precise and unambiguous quality standards
- the specific application of ISO9001 to the ready mixed concrete industry
- product conformity criteria designed to achieve effective control of risk at minimum cost
- industry bench-marking data against which companies can judge their own performance
- liaison with major specifiers and contractors to resolve industry-wide issues
- access to the UK’s technical experts in the field of ready mixed concrete.

If the concrete suppliers are working to achieve better efficiency why is it that in the UK the customer has not adopted better management and working practices to ensure that he also is taking advantage?
2.2 Many issues still need to be addressed

Increased productivity is key to any construction activity. The use of fewer resources, with less waste being created is critical to this.

In their paper, Anson and Shouging (1994) put forward proposals to improve the productivity of a concrete operation. Their research found that the supply of concrete to a construction site is the most important variable that management could attempt to control. Consequently, great emphasis is placed on the 'real-time' management of concrete placing.

Anson and Shouging's research was based on a study of 137 pours, each observed from start to finish, on buildings in Hong Kong between spring 1991 and spring 1993. The 137 pours included 51 pumped pours; 43 pours placed by crane and skip (craned); and 43 placed by hoist and barrow (barrowed). The relevant statistics for the three methods were compared and thus performance yardsticks or benchmarks were defined.

Of particular interest to this thesis are the values established for the time spent waiting for concrete. The following interruptions in supply were found for:

- Pumped pours = 12.1%
- Craned pours = 11.9%
- Barrowed pours = 12.6%

Therefore it can be concluded that approximately 12% of the entire pour time is spent waiting for concrete. Anson and Shouging had found a similar figure in Germany, with 11% of the overall pour time being spent waiting for concrete.

On the other hand, the values Anson and Shouging have derived for the UK compare somewhat less favourably. They discovered an average of 25% of the pour time to be typical. An immediate comparison of those values suggests that the UK is lagging behind in obtaining an efficient supply of concrete.
It is possible to argue that values for the UK should not be compared with values for Hong Kong and Germany. After all different countries have very different industrial structures and therefore different methods of working. However, with regard to concrete pouring, it is clearly apparent that working methods are comparable. Anson and Shouging show that the pouring methods used in the three countries are very similar, as are the trucks that deliver the ready mixed concrete to the site. Therefore, it is their intention to provide good performance yardsticks that are relevant not only for Hong Kong, but also in other developed countries, such as the UK. They write:

“Yardsticks are useful as a means of improving performance overall on the ‘pulling up by the bootstraps’ principle. Sporting records are continually being improved upon, no doubt partly because targets exist and are well known to all athletes involved.” (Anson and Shouging 1994)

This statement suggests that Anson and Shouging believe it is possible to continuously improve upon efficiency through striving to meet targets in much the same way as an athlete might.

Although Anson and Shouging focused on yardsticks primarily as a method of comparison, the usefulness of their paper for this thesis lies in the fact that further deductions can be made. For example, such yardsticks, at the very least, demonstrate the level of efficiency that should be obtainable in the UK. In addition benchmarks can act as performance incentives. Therefore they could be considered as part of a solution to reduce wastage in concrete operations in the UK.

The ultimate aim of this research is to investigate ways in which concrete placing can be planned and managed efficiently. Anson and Shouging may have shown how yardsticks can be of benefit to the construction industry, but their paper does not attempt to provide solutions to how site teams could reach targets. Therefore, the remainder of this literature review will investigate other sources for such solutions. Firstly, it will examine different techniques available to study the concrete placing process and discuss recent developments in planning and then developments in management.
2.3 Design of assessment models considered

In an effort to improve the efficiency of concrete operations, academics have given a great deal of consideration to the development of improved methods for planning. However as planning encompasses such a wide area, different writers have focused on different elements of planning. In order to accurately mirror what happens on constructions sites many different approaches have been studied. One of the first steps in this research project was to identify different techniques available that would readily allow the investigation of the concrete placing process. Those identified are listed below and discussed in further detail in this chapter.

1. Simulation analysis,
2. Regression analysis,
3. Queuing theory,
4. Lean construction,
5. Concurrent Engineering, and
6. Neural Networks.

2.3.1 Simulation Models

Computer simulation is the process of designing a mathematical logic model of a real system and experimenting with this model on a computer (Pritsker et al, 1997).

Banks and Carson (1984) warned that even if the model structure is valid, if the input data are correctly collected, inappropriately analysed, or not representative of the environment, the simulation output data will be misleading and possibly damaging. Abourisk and Halpin (1992b), two of the most prominent researchers in this field, concurred with Banks and Carson (1984), and highlighted the requirement for the correct application of theoretical probability distributions. It is these probability distributions that ultimately reflect the raw data and form the basis for the simulation model.

Smith (1998) used discrete-event simulation to model the concrete placement system. The state of the system is represented by variables and the basic principle is to reflect the changes of the state of the system as they occur at discrete events. The events are the arrival and the
departure of concrete truckmixers in the system and only these events can change the state of the system. In the researchers model the state variables were the number of trucks in the queue, the state of the concrete pump (idle or busy), the departure time of the next truckmixer and the arrival of the next truckmixer.

Smith (1998) suggested that at the heart of a discrete-event simulation tool is the random variate generator (the researcher used the GA algorithm to generate gamma variates). It is used to compile an event list from which the simulation programme is run. The event list is an array in the computer’s memory, which shows in chronological order, the type and time of the next event that occurs. The concrete placing model was analysed using Visual Basic for Applications (VBA) coded into a Microsoft Excel spreadsheet.

Smith (1998) suggested that discrete-event simulation allows easy changes to the model for different operating conditions and allows the investigator to look at the raw data easily, either directly from the generated spreadsheets or via charting functions.

Smith (1999a) extended the discrete-event simulation study of concrete placement processes by undertaking a factorial design experiment. The aim of the experiment was the investigation of the main factors influencing the cost and productivity of the process.

Computer simulation packages have been used for many years and are being constantly updated. The first major computer package for construction operations was CYCLONE by Halpin (1977). Since its introduction, construction simulation has been advancing with computer technology (Shi, 1999a). Various construction simulation languages have been developed. Naji and Najafi (1996) suggested that there are two main simulation methodologies, the network- based simulation and the graphical simulation technique. Opdenbosch and Baker (1994) criticised network-based simulation claiming it has failed to describe three main factors that influence most construction operations; (1) the construction site; (2) the geometry of building, and; (3) the dynamics involved in operating construction equipment. Due to these reasons, Naji and Najafi (1996) suggested that the graphical simulation technique is gaining support within the construction industry.
Examples of network-based methods include INSIGHT (Paulson, 1978; Paulson et al 1987), STROBOSCOPE (Martinez and Ioannou, 1994), CIPROS (Tommelein and Odeh, 1994), RESQUE (Chang, 1987) and UMCYCLONE (Ioannou, 1984). Alternatively, DISCO (Huang et al, 1994) and COOPS (Liu and Ioannou, 1992) provide graphical interfaces to allow the user to construct a simulation model by manipulating graphical symbols on a computer screen (Shi, 1999a).

Shi (1999a) proposed an alternative to computer simulation systems such as those mentioned above. This alternative system is known as an Activity-Based Construction (ABC) Modelling and Simulation method. ABC modelling (ABC-Mod) uses one single element (e.g. activity) for modelling general construction processes, instead of multiple elements as required by current simulation systems. ABC simulation (ABC-Sim) executes the ABC model by manipulating activities in three stages: (1) Select activity, (2) Advance simulation, and (3) Release simulation entities.

Shi (1999a) ran a simulation methodology comparison experiment between ABC-Mod and CYCLONE, and reported that the ABC model uses only five activities in comparison to CYCLONE's fourteen. The researcher concluded that ABC-Mod is more easily understood and the philosophy of ABC-Mod is such that it enables an engineer to construct a simulation model for a familiar construction process.

Hajjar and AbouRizk (2002) use Special Purpose Simulation (SPS) Modelling which stipulates that computer simulation tools must enable a practitioner, who is knowledgeable in a specific construction domain but not necessarily in simulation, to model a project within that domain in a manner where graphical representations, navigation schemes, specification of the model parameters, and representation of simulation results are completed in a format native to the domain itself. The underlying assumption with SPS is that a knowledgeable developer can develop a set of specialised modelling elements or building blocks for a given domain that are easy to understand and flexible enough to allow someone else to construct simulation models in that domain.

Lu (2003) presents an excellent paper using research based on the Simplified Discrete-Event Simulation Approach (SDESA). The SDESA is presented through extracting the constructive
features from the existing event/activity-based simulation methods; both the algorithm and the model structure of simulation are streamlined such that simulating construction systems is made as easy as applying the critical path method (CPM). Two applications based on real road construction projects serve as case studies in the paper to illustrate the methodology of simulation modelling with SDESA and reveal the simplicity and effectiveness of SDESA in modelling complex construction systems and achieving the preset objectives of such modelling.

Simulation analysis is a very powerful tool that if used carefully can yield very good results. Based on the advantages that the method is relatively straightforward to implement, and that it has yielded good results for similar problems in the past, it shall be investigated further as part of this project. Simulation analysis is therefore presented and discussed in more detail in Chapter 6.

2.3.2 Regression analysis

Regression analysis is a powerful tool that enables the researcher to learn more about the relationships within the data being studied and has been used by various researchers. It is one of the most widely used statistical tools and in its simplest form, regression analysis is a statistical method used to determine the relationship between two or more variables (Birkes, 1993). There are many texts that describe this technique and the theory behind its use but Hogg and Ledolter (1992), was found to be one of the most comprehensive texts.

Birkes (1993) proposed the following assumptions relating to regression analysis:

- In the underlying population, the relationship between the input and response should be a straight line.
- For each value of input, the variation in the population of responses should be approximately the same.
- For each input value, the distribution of the responses in the population should be approximately normal.
- The responses that are obtained should be approximately independent.

Regression analysis can take many forms, two of the most common techniques are:
1. *Simple regression analysis* were the relationship between the explanatory variables and response are analysed and a model formed, and

2. *Stepwise multiple regression analysis* were one by one the explanatory variables are either added or removed from the model depending on their significance. The advantage of this technique is that only those explanatory variables that are significant to the response variable remains in the final model.

Hogg and Ledolter (1992) suggested the following methodology for the application of stepwise multiple regression analysis:

1. Regression equation fitted to variables.
2. Decision made as to whether all explanatory variables are significant.
3. If variable is significant it remains in the model, otherwise, it is removed and the regression analysis is repeated.

Further methods of regression analysis are presented by Goh (1999). The researcher used multiple linear regression (MLR), multiple log-linear regression (MLGR) and autoregressive non-linear regression (ANLR) to predict construction demand in Singapore.

Birkes (1993) suggested that it is important to know whether there is evidence of statistical significance between two input parameters and the response. The researcher stated that the t-ratio is compared to the general Student’s t-distribution function with the required significance level and number of degrees of freedom.

Brubaker and McCuen (1990) provided a brief overview of the prominent hypothesis tests used in engineering, but they also suggested that the level of significance used in such tests is usually arbitrary. The researchers concluded that this choice could result in irrational and imprecise models.

Smith (1999b) developed a regression model that provided an equation, which described over 90% of the variance in a large set of data obtained from different sources and provides a realistic estimate for the actual output from excavator/dump-truck earthmoving operations.
Dunlop and Smith (2001) compared actual productivity rates for concrete pouring activities with results from lean construction principles, information from a professional planner and a regression analysis model. The researchers concluded that regression analysis, using the seven most significant variables, has provided an equation that describes 80% of the variance in the large set of data obtained from real concreting operations.

Goh (1999) concluded that non-linear regression techniques are more accurate in representing the complex relationship between demand for construction and its various associated indicators. Furthermore, in addition to improved accuracy, the use of non-linear forms also expands the scope of regression analysis.

It can be seen that Regression Analysis is a powerful tool which has been used in investigating similar problems in the past and therefore deserves further consideration. Its advantages include the fact that many computer packages can apply this technique (for example, Microsoft Excel) and provide models which are in fact no less powerful than those developed using more advanced techniques, such as Neural Networks which shall be introduced later. Regression analysis and modelling shall be introduced later in this thesis, in Chapter 5.

2.3.3 Queuing theory
Saaty (1961) described queuing theory as a branch of applied mathematics, which utilises the concepts from the field of stochastic processes. Saaty stated that it has been developed in an attempt to predict fluctuating demands from observational data and to improve the understanding of a queuing situation, enabling better control.

In many ways, queuing theory appears to be the perfect tool for modelling concrete placing operations and a great number of academics have applied queuing theory to various problems. Below is a brief summary of some of the methods presented by these researchers:

Jackson (1963) developed the product form equilibrium distribution. This distribution describes the number of items at nodes in a performance model. Gribaudo and Sereno
Jackson's findings as one of the most important analytical results that has been developed to solve queuing problems. Morse (1955) presented papers discussing the application and solution of the transient behaviour of a simple queuing system with exponential distributions on service time, with constant mean service rate. The researchers suggested the use of explicit equations in the solution of queuing situations. This is criticised by Leese (1967), who stated that even in simple cases, the explicit formulae are quite complicated and are not very suitable for numerical work.

Carmichael (1987) developed a queuing model that he claimed accurately reflected the variability in the plant cycle times as well as plant interaction in earthmoving operations of the shovel-truck and pusher-scraper types. The researcher represented the $(E_n/E_m/1)/K$ finite source queuing model by using Erlang distributions (with shape parameters $h$ and $m$ respectively), $K$ represents the number of trucks or scrapers, and $1$ implies one shovel or pusher.

Carmichael (1987) suggested the solution to a finite source queuing model is to use an equivalent two-stage cyclic queuing representation, where one stage represents the back-cycle stage and the other the loading/service stage. Superimposed on this representation, is a state definition that is one-dimensional for each stage, leading to a total two-dimensional state for the whole operation.

Van Dijk (1993) suggested that queuing networks are flexible and have generic modelling capabilities, and further suggested that these traits have attributed to the success of queuing models. However, Williams (1996) stated that apart from product form networks (i.e. those for which the output state probability is expressed as a product of the individual queue state probability), most queuing networks have not proven amenable to exact analysis. This view is agreed with by Carmichael (1987) who claimed that queuing models have always been restricted by the assumption of unrealistic probability distributions. Gribaudo (1998) criticised Williams' (1996) view that product forms are accurate. The researchers stated that although they are easy to use, product form distributions seldom satisfy the associated conditions, and hence, rarely provide exact solutions.
Queuing theory is useful in that it allows the concrete placing system to be understood in terms of servers and clients. In this respect, both queuing theory and simulation use the same language. However, the research seems to suggest that its implementation can be difficult and unpredictable and therefore a decision on its usefulness as applied to this study was reserved until after other tools had been investigated. Subsequently, apart from using it as a basis for representing the concrete placing system as a queuing system, queuing theory was not implemented as other methods were found to be acceptable.

2.3.4 Lean construction
Lean construction has been developed from management principles used by Toyota, led by Engineer Ohno, who doggedly set about eliminating waste in the car manufacturing industry. The term ‘lean’ was coined by the research team working on international auto production to reflect both the waste reduction nature of the Toyota production system and to contrast it with craft and mass forms of production (Womack et al., 1991) Whilst lean production was successful in the car manufacturing industry, many believed that it would not be applicable in the dynamic world of construction. Of course, a great deal of work has been carried out in this area with many favourable findings.

Lean construction advocates the elimination of waste whilst using fewer inputs. Howell (1999) states that moving towards zero waste, perfection, shifts the improvement from the activity to the delivery system. While much work has been carried out concerning particular activities, the delivery system is regularly being overlooked. Lean principles, such as ‘Just-In-Time’ (JIT) delivery has gone some way in addressing this issue. Tommelein and Li (1999) have been active in this area and have explained concepts underlying a just-in-time production system. A further ‘lean’ principle is the analysis of all operations as a series of flow and conversion activities (Koskela, 1992). Conversion activities are those operations performed in adding value to the material or information being transformed to a product. Flow processes represent activities such as inspection, moving and waiting. This is an ideal model on which to base the investigation of concrete operations.

Lean construction is seen by some as a panacea to all construction’s woes and as such it deserves further attention. Whether it can be directly applied as a tool for managing concreting operations, or whether it is merely a philosophy that is placed over such
management activities remains to be seen and Chapter 4 will provide a further critical review of this field.

2.3.5 Concurrent engineering
The application of concurrent engineering (CE) philosophies to the construction industry follows on from many other manufacturing and production based approaches developed to aid the industry. In many ways concurrent engineering is similar to lean construction.

They all have one ultimate aim and that is to make construction ventures more efficient and effective, both financially and on time. However, CE tools introduce a new level of understanding and management techniques that have perhaps been overlooked in the past.

Many researchers have defined concurrent engineering; Winner et al (1998) define concurrent engineering as

‘a systematic approach to the integrated, concurrent design of products and related processes, including manufacture and support. This approach is intended to cause developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements’

Dean and Unal (1992) capture the true essence of CE as

‘getting the right people together at the right time to identify and resolve design problems. Concurrent engineering is designing for assembly, availability, cost, customer satisfaction, maintainability, manufacturability, operability, performance, quality, risk, safety, schedule, social acceptability, and all other aspects of the product’.

The above definitions of CE at first glance may appear to be pertinent; however, if CE is to make a difference and be embraced by the construction industry all of these factors must be taken into account at the earliest possible opportunity. To achieve this it is necessary to include as many people, from all disciplines, at this early stage. CE advocates that simultaneous consideration of all life-cycle phases using a multi-disciplinary approach must be incorporated (Kusiak, 1993). By doing so effectively a reduction in cycle times, by
increasing the degree of integration amongst the activities, can be expected. This will have great benefits on many construction projects as many tend to be engaged in a concurrent environment.

Concurrent Engineering appears to be, like Lean Construction, more of a philosophy than a direct tool. Its appropriateness to concrete placing cannot, however, be ignored and from this respect a paper was prepared and presented at the 8th International Conference on Concurrent Engineering in 2001. Following the success of Simulation and Regression Analysis it was subsequently decided that concurrent engineering would no longer be pursued.

2.3.6 Neural networks
Haykin (1994) defined a neural network as a machine that is designed to model the way in which the human brain performs a particular task or function of interest. It is made up of a complex network of artificial neurons or processing elements (PE) (Hua, 1996).

Like a neuron, the PE performs three basic functions. Firstly, it receives inputs from other PE’s through weighted links; secondly, it processes these inputs; and finally, it outputs the results to other PE’s.

Mathematically, a neural network is defined by Boussabaine and Kaka (1998) as:

\[ \text{Output Node} = \sigma \left[ \sum W_{ij} X_j(t) - \beta \right] \]

Where, \( \sigma = \text{sigmoid function} \), \( W_{ij} = \text{strength of the connection (weight) from node } j \text{ to node } i \), \( X_j(t) = \text{output value of node } j \), \( \beta = \text{node threshold} \)

And, \( \sigma = 1/(1+\exp(-\beta x)) \), \( \beta = \text{steepness of the sigmoid function} \)

Shi (1999b) suggested the following steps should be implemented in the development of a neural network-based system:

1. Analyse the real world problem and select the network architecture.
2. Collect and pre-process data for training and testing.
3. Design, train and test the network model.
4. Deploy the network.

This method of development is supported by Boussabaine (1996), and Chao and Skibniewski (1994). However, Chao and Skibniewski (1994) suggested some differences in the methodology. These are:

1. At the train and test stage, use the portion of the prepared data as a training set for the respective neural network and assign network parameters to start training. Use the rest of the data to test the performance of the trained network. Define the acceptable prediction errors. Improve the performance of a network by adjustments of network parameters over several trials.
2. At the deployment stage, implement the application of the networks via a query and answer program.

Flood and Kartan (1994) suggested that neural networks should not be implemented as an alternative to conventional computing techniques, but as a complement. This view was disagreed by Dutta and Shekbar (1988), who claimed that in problems with non-conservative domains, better solutions are provided by neural networks than by conventional methods.

Haykin (1994) offered a selection of useful properties and capabilities of neural networks. They are as follows:

1. Non-linearity
2. Input – output mapping
3. Adaptivity
4. Evidential response
5. Contextual information

A further useful property of neural networks was provided by Bolt (1992). It is as follows:

- Fault tolerance: A neural network has the potential to be inherently fault tolerant. If a neuron or its connecting links are damaged, recall of the stored information is
impaired in quality. However, owing to the distributed nature of information in the network, the damage has to be extensive before the overall response of the network is degraded seriously.

In contrast to the reported capabilities of NN's, McCabe (1997) suggested that they have an inflexible input-output structure, in that an entirely new network is required if any variables are deleted or added. Furthermore, any additions will require complete retraining of the network.

Chao and Skibniewski (1994) claimed that neural networks are able to model the complex relationships between the job conditions and the probability of an operation, in relation to construction activities. The researchers concluded that neural networks achieve an acceptable level of accuracy in estimation. This view is shared by Rummelhart et al (1994). Hua (1996) supported the views of Chao and Shibniewski (1994) on the accuracy of neural networks. In Hua's (1996) comparison study between neural networks and multiple regression analysis, the conclusion was that the forecasting error of the neural network was equal to 0.20 that of the multiple regression model. McKim (1993) also supported the view that neural networks out perform traditional statistical methods.

Interestingly, Zayed and Halpin (2004) carried out a study into the installation of piles. They compared four different techniques: deterministic, simulation, multiple regression and artificial neural networks (ANN), and assessed there individual ability to solve the same problem. The result of this comparison shows that the ANN is probably the appropriate technique that assesses the piling process outputs. Regression models rank second with a slight difference from the ANN. Simulation is third with the deterministic approach someway back in fourth. What is very interesting from this study is the realisation that whilst ANN's only slightly outperform multiple regression for this particular dataset, multiple regression was found to be the most user friendly.

Flood and Kartan (1994) contradict all these opinions by implying that neural networks produce inexact results, a lack of theory to guide selection of the most appropriate size and configuration of the network, and slow progress during training. Flood (1993) suggested
that the inaccuracies of neural networks must be minimised before they can realise their full potential.

Boussabaine and Kaka (1998) expressed that further research was necessary before the conclusion that neural networks are more accurate than traditional methods can be drawn. This has been the general conclusion made from the literature review of Neural Networks: it will be a technique that is 'held in reserve' if other techniques fail to represent the system appropriately. There is little point in implementing a complex and difficult to manage model if it produces solutions no more useful that other, simpler techniques.

Table 2.1 below summarises the main strengths and weaknesses of the techniques considered above.
Table 2.1: A comparison of potential methodologies for investigating concrete placing

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Strengths</th>
<th>Weaknesses</th>
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<tbody>
<tr>
<td>Simulation analysis</td>
<td>• Successfully used in other similar problems</td>
<td>• Requires extensive dataset to provide input distributions</td>
</tr>
<tr>
<td></td>
<td>• Methodology simple to understand</td>
<td>• Requires either bespoke software or specialist computer packages to run</td>
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<td></td>
<td>• Flexible</td>
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<tr>
<td>Regression analysis</td>
<td>• Very easy to implement</td>
<td>• May not provide appropriate model</td>
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<td></td>
<td>• Models developed via a variety of computer packages</td>
<td>• Models, once developed, not flexible for different operation conditions</td>
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<tr>
<td></td>
<td>• Needs no specialist software to use</td>
<td>• Non-linear problems much more difficult to solve</td>
</tr>
<tr>
<td>Queuing theory</td>
<td>• Describes the concreting process usefully as a queuing process</td>
<td>• Solutions difficult to achieve</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Complex theory difficult to understand, especially by non-specialist construction practitioners</td>
</tr>
<tr>
<td>Lean construction</td>
<td>• Gaining acceptance as a method of improving construction</td>
<td>• A philosophy rather than a tool</td>
</tr>
<tr>
<td></td>
<td>• Useful for describing construction at the project, or macro, level</td>
<td>• Usefulness and effectiveness not tried and tested at the construction process, or micro, level.</td>
</tr>
<tr>
<td>Concurrent Engineering</td>
<td>• Gaining acceptance as a method of improving engineering</td>
<td>• Appropriateness in construction at the macro or micro level</td>
</tr>
<tr>
<td>Neural Networks</td>
<td>• Powerful and can describe very complex processes</td>
<td>• Requires complex programming and/or specialist software to implement</td>
</tr>
<tr>
<td></td>
<td>• Allows models to be developed for even the most non-linear of processes</td>
<td>• May provide models that are no more accurate that simpler techniques.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Requires large dataset for training, testing and validation</td>
</tr>
</tbody>
</table>

Having embraced the extensive literature available regarding the tools and techniques available to help analyse concrete placing operations, it was realised that similar construction activities exist that may hold some key answers to the best approach to adopt. These are discussed in the next section.
2.4 Earthworks – a related field

A comprehensive solution to improving the efficiency of concrete operations through planning has not yet been discovered. Therefore, it is necessary to widen the scope of investigation for this research project to include an examination of related fields that may hold such a solution. For example, the simulation of earth-moving operations can assist in providing measures that might improve the efficiency of concrete placing operations. Smith et al. (1995) describe the problems that are experienced in earthworks:

"On very large contracts the total number of separate earth-moving operations can be very high and this, coupled with tight budgets and completion target dates, means that the earthworks should be planned as well as possible before site works start .... If the resources are incorrectly calculated large additional cost can be incurred once work has begun ...."

and,

"The contractor needs to plan and estimate an earth moving operation as accurately as possible... and to control site operations to keep costs to an absolute minimum"

These extracts show that similar problems do in fact exist in earthworks as in concrete operations. Furthermore, the repercussions of poor planning provide the same incentives to become more efficient.

If the control of wastage in earth-moving operations gives rise to the same concerns as in concrete operations, it is likely that proposals to improve the efficiency of earthworks may be relevant to concrete operations.

The research of Smith et al. (1995) argues that improvements in the estimation of productivity of an operation can be made at the planning stage to reduce wastage through a better tender price and estimation of plant required. Therefore, the paper intends to determine accurately the earth-moving productivity, numbers of plant required and the costs.
To calculate the productivity of a single earth-moving hauler, its cycle time is required. The more accurate the calculated cycle time, the better the production estimate will be. Therefore, the component parts of a cycle were studied separately. These were:

- Load time
- Haul time loaded
- Dump time
- Haul time empty
- Wait time
- Manoeuvre or spot time

From the observed times, the actual length of time for load, wait and cycle can be readily determined. This was used immediately to calculate an average production rate for the period of observation. The production rate could then be given to the contractor to help with production control. Indeed, excessive over- or under-resourcing would be immediately apparent.

Smith et al. (1995) intend that the ideas and data presented here can be used before operations on site begin to achieve an accurate tender price and a better estimate of the amount of plant required. It should not be difficult to demonstrate to site teams and contractors how the estimates are derived. In this respect the proposals of Smith et al. (1995) represent a more practicable planning tool than the complex sequencing methods which have been discussed.

2.4.1 Optimising earth moving operations

Jayawardane and Price (1994) make a further attempt at a comprehensive approach to planning. The paper explores a procedure to optimise earthwork operations in road construction by combing computer simulation models and linear programming.

Advanced techniques such as computer simulation are available to overcome the overestimation of production obtained by deterministic methods, although its use is limited due to various constraints. Parallel to these developments, linear programming models have
also evolved to optimise earthwork allocations. However, these existing models fail to test alternate plant teams or incorporate constraints such as the total project duration. Therefore, Jayawardane and Price have designed a model that extends the capabilities of computer simulation and linear programming, and combines them to optimise the entire earthmoving system.

Jayawardane and Price's (1994) proposed methodology consists of three stages, each of which includes several steps. It is apparent that their proposal deals with a wide scope of issues in earthmoving operations, therefore, the three stages will only be summarised below.

Stage 1. Individual simulation
Identify all feasible haulage operations
Identify all possible plant teams and test for each operation
Identify appropriate Swell/shrinkage factors corresponding to different soil types and operating conditions
Identify shift times and official breaks
Perform individual simulations and obtain realistic unit earthmoving costs for each haulage operation corresponding to plant teams tested under prevailing operating conditions

Stage 2. Linear/integer programming (LP/IP) optimisation
Identify cut quantities required along the roadway corresponding to operating conditions
Obtain capacity limitations of borrow/disposal sites, and their setting up costs
Obtain project duration and other constructional restraints
Apply proposed LP/IP model based on the unit costs obtained in stage 1 to obtain optimum material distribution selecting appropriate borrow/disposal sites, optimum plant teams for individual operations from available resources satisfying all constraints

Stage 3. Network scheduling
At this stage the results obtained at the end of stage 2 should be applied together with the sequential logic of the construction operations in the LP/IP formulation in order to obtain a construction schedule.

The paper concludes that the main outputs of the model should provide:
Optimum material quantities
Optimum combination of plant teams
The minimum time during which the project can be completed

2.4.2 The total cost
The proposal made by Jayawardane and Price (1994) is based on a solid perception. They have observed that those two powerful techniques - computer simulation and linear programming can be combined in order to overcome their individual limitations. In addition, as is demonstrated from the outlined methodology, the solutions deal with a wider scope of issues in planning than Kunigahalli and Russell (1995) who concentrated only on sequencing.

Their system becomes less valuable when it is recognised that the three stages in the methodology entail a very lengthy procedure. As a more appropriate solution would be one that is comprehensive, yet practical and swift to implement, further investigation is still required.

As has already been said, research into improving the efficiency of concrete operations is fairly scarce - the investigation of related areas such as earthworks have been particularly useful. Nevertheless, what these papers do show is that planning is an area where a good deal of progress is being made. However, if an initial point made in Smith et al. (1995) is considered, an important observation can be drawn. Smith et al. (1995) state in relation to earthwork systems:

“It was found that the actual travel times were 21% longer, on average, than the calculated times.”

This statement illustrates the fact that in planning for operations, theoretical calculations are often an unrealistic representation of actual site performance. Such inaccuracy can be assumed to be a consequence of calculations that are based on best performance times for plant and labour, which does not take into account the problems and delays that are inevitable on a construction site.
2.5 Asphalt Placing - a related field

The nature of asphalt operations dictates that solutions to improve efficiency and make financial savings are based on achieving a smooth cycle with minimum interruptions, through real-time management. In their paper Pagdadis and Ishai (1994) support this argument with the following statements:

"to achieve an integrated cycle, the site process must be controlled in real time"

and,

"a continuous travel condition is achieved with minimal delays .... but also to improve product quality and overall economy."

Similarities between asphalt and concrete operations can also be drawn from the outcome of an efficient cycle. That is to say, that in both sectors efficiency promotes financial savings and improved quality of the final product.

This becomes more interesting when it is considered that in several further ways concrete placing has more in common with asphalt placing than with earthworks. For example, if too much time is allowed to elapse between placements both concrete and asphalt will set and be rendered useless. Another parallel is that both concrete and asphalt have to be transported with care, as any unintentional deposits must be written of as wastage.

Pagdadis and Ishai (1994) explain that real-time management solution requires design standards, field data collection, field management, site restraints, and project designs to be handled together. Therefore, Pagdadis and Ishai (1994) have developed a Site Operations Control System to overcome the present data handling complications, which preclude the process from being achieved in real-time.

A similar system may well provide benefits to concrete operations. By allowing the site team real-time access to all the information required, technical obstacles that occur could be effectively overcome. This would be particularly beneficial on large construction sites where
delays occur because of the time it takes for the engineer to make the journey to the site office to find the required information.

Asphalt placing appears to be in many ways similar to concrete placing operations, but like concrete operations there appears to be a limited amount of research in this particular area. It may be worth noting that this is a possible avenue for further research.

2.6 Chapter summary

Due to a realisation that the performance within the construction industry in the UK is lagging behind many of the world’s advanced countries, an effort has been made to promote efficiency. Worldwide research into how the construction industry performs has taken place for many years, but until recently much of this has occurred outside the UK.

In this chapter, current practices of concrete delivery and placement in the UK have been analysed and key areas for further study have been introduced. Having identified the areas that require further attention, it was necessary to search for the best tools and techniques in order to further study the process. These were found to be:

1. Simulation analysis,
2. Regression analysis,
3. Queuing theory,
4. Lean construction,
5. Concurrent Engineering, and
6. Neural Networks.

On reflection, all of the above techniques have distinct advantages and disadvantages. For the remainder of this thesis only simulation analysis, regression analysis, lean construction, and to a lesser extent queuing theory, have been utilised, and in the following chapters these are discussed in more detail.

During the course of this research project Concurrent Engineering was studied in some depth and from the work carried out in this area a conference paper was written and
presented at the 8th International Conference in Concurrent Engineering, in Anaheim, California (Dunlop and Smith, 2001).

At the University of Edinburgh, Forbes et al (2004) carried out further research into the uses of Neural Networks for the analysis of the concrete delivery and placement process. Forbes et al (2004) used the same dataset as was used in this research and it was found that neural network modelling does offer an alternative method of analysis.
Chapter 3
Data Collection and Outline of Key Characteristics

The five construction projects studied are detailed and the data collected from them is explained. This data is then subjected to statistical analysis and the trends are discussed and analysed. It is found that there are several factors that affect on-site productivity and these are discussed in detail.
Chapter 3 Data collection and outline of key characteristics

To understand concrete operations as fully as possible, the first step was to simply observe and record real concrete operations. The observation of real concrete operations was undertaken for approximately nine months and the subsequent dataset collated is arguably one of the largest and most complete available to researchers in the UK.

In order to accurately collect the data required from the concrete operations, work-study techniques were used which required full consultation with all the site personnel involved. It was important to be open and honest with those operatives that were ultimately being watched and assessed in order to avoid conflict and unnatural working habits. This ensured that any conclusions drawn from the observations could be relied on and used in any subsequent model. Five major civil engineering projects, involving varying volumes of concrete pours, have been used in this study to various degrees and the raw data gathered from them form the basis for any model and solutions proposed in this study.

This chapter describes the sites studied along with the key characteristics and findings encountered during data collection. The initial data from the site observations will also be presented along with some of the early findings.

3.1 Sites Studied

This study is based on five projects, constructed and observed between June 1993 and March 2002. Each project had very different attributes and features but had one thing in common and that was an abundance of structural concrete. The project from 1993 and 1994 was the initial data and reflects historical data that many contractors will have in their archives. The final four projects ranging from January 2000 to March 2002 allowed the investigator to observe all pours. Four of the projects were based in Scotland and one was in the North of England.
Each project will be discussed in turn, paying particular attention to number and type of pours, location and location of supplier relative to the site.

3.1.1 M6 Thelwall Viaduct
The first project studied was the M6 Thelwall Viaduct, Cheshire, England which commenced in early 1993 and completed mid 1994. Tarmac Construction Ltd. (now part of Carillion Plc) undertook all of the construction work with the client being the Highways Agency. The project involved the construction of a motorway viaduct and widening and included a wide range of concrete pours – from very large base pours to small narrow columns. For the whole project the pours ranged in size from 2 m$^3$ to 1200 m$^3$ providing a wide spectrum of pours.

The concrete was supplied from three different sources: two offsite batching plants and one, providing the majority of fresh concrete, onsite. All were owned and operated by Tarmac Topmix. An onsite batcher would be very common on larger construction projects with vast volumes of concrete or where work was being carried out in built up areas with very limited scope for access roads. The other two concrete batching plants at Warrington and Bredbury (see Figure 3.1) were mainly used on days when particularly large quantities of concrete were required or as a back up for the on site batcher during breakdowns etc. All concrete pours recorded represented pours that used a mobile concrete pump to place the concrete.

The data from this project was used in the initial stages of this study and as the project dates back to 1993/4 it was necessary to rely on historical data collated by Tarmac Construction Ltd (see Figure 3.2). It is common for contractors to keep concrete pour records as they can be very useful not only as a basis for estimating future pours but also in cases of litigation.
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Figure 3.1: Map showing M6 Thelwall site and the location of the Warrington batching plant used
(Multimap, 2005)
<table>
<thead>
<tr>
<th>Ticket Number</th>
<th>Vehicle Reg No.</th>
<th>Source</th>
<th>Concrete</th>
<th>Slump (BS 1881:1983)</th>
<th>Cubes (BS 1881:1983)</th>
<th>Quantity</th>
<th>Air</th>
<th>Temp</th>
<th>Slump</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>T123</td>
<td>E200</td>
<td>S1B</td>
<td>Batch</td>
<td>11.65</td>
<td>11.37</td>
<td>T</td>
<td>G</td>
<td>70.5</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>T456</td>
<td>E300</td>
<td>S1B</td>
<td>Arrive</td>
<td>12.07</td>
<td>12.28</td>
<td>T</td>
<td>G</td>
<td>68.5</td>
<td>21.0</td>
<td></td>
</tr>
<tr>
<td>T789</td>
<td>E400</td>
<td>S1B</td>
<td>Start</td>
<td>13.21</td>
<td>13.42</td>
<td>T</td>
<td>G</td>
<td>63.2</td>
<td>12.5</td>
<td>C 2094</td>
</tr>
<tr>
<td>T123</td>
<td>E200</td>
<td>S1B</td>
<td>Complete</td>
<td>12.20</td>
<td>12.43</td>
<td>T</td>
<td>G</td>
<td>61.5</td>
<td>12.0</td>
<td>C 2095</td>
</tr>
<tr>
<td>T456</td>
<td>E300</td>
<td>S1B</td>
<td>Sample</td>
<td>13.30</td>
<td>13.58</td>
<td>T</td>
<td>G</td>
<td>57.5</td>
<td>10.0</td>
<td>C 2096</td>
</tr>
<tr>
<td>T789</td>
<td>E400</td>
<td>S1B</td>
<td>Test</td>
<td>13.80</td>
<td>14.09</td>
<td>T</td>
<td>G</td>
<td>52.5</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Time</td>
<td>14.30</td>
<td>14.54</td>
<td>T</td>
<td>G</td>
<td>47.5</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Type</td>
<td>14.40</td>
<td>14.64</td>
<td>T</td>
<td>G</td>
<td>42.5</td>
<td>10.0</td>
<td></td>
</tr>
</tbody>
</table>

Slump Type - (T)rue / (S)hear / (C)ollapse
Air Test To BS 1881:106:1983
Programme Start...89.89

Slump Method - Alternative / General
Concrete Sampled To BS 1881:101:1983
Actual Start...107.14

Weather....OVERCAST....Mix Specified...SOAR...Cement type...PERC...Admixture...Cement A

Total Order 130 m³
Cement Content 430 kg/m³
Method of Place...Rumpe...Design Slump...60 mm

BS 5328 Slump Limits 55-145 mm
Air Limits N/A...Operator...Rumpe...Signed...Mal

Page 2 of 2
3.1.2 Tay Wastewater Treatment Works

The second project, and the first that this investigator actually observed from start to finish, was the Tay Wastewater Treatment Works project in 2000. The Tay project was the second wastewater treatment scheme undertaken by North of Scotland Water Authority (NoSWA) to be procured using the Government’s Public Private Partnership procurement route. NoSWA entered into a contract with Catchment Tay Ltd, a private consortia, to provide wastewater treatment and disposal facilities for the City of Dundee, Broughty Ferry, Monifieth, Carnoustie and Arbroath.

The scheme would primarily enable interception of foul flows from 41 outfalls, which previously discharged into the Tay Estuary and lower Angus coast, although some will be retained for storm water overflows. This was undertaken by the design and construction of a series of new collection pumping stations and transmission pumping mains together with a new wastewater and sludge treatment plant at Hatton (Hatton WTP) situated between Arbroath and Carnoustie, see Figure 3.3. The final effluent from the Hatton WTP will flow through a new long-sea outfall whose discharge point is located 1.6 km offshore.

Catchment Tay Ltd. would bear the design, construction, operation maintenance and financing risk associated with the scheme which had to comply with discharge consents and water quality standards enforced by the Scottish Environment Protection Agency. Catchment Tay Ltd. is a consortium consisting of Bechtel Water Technology, Morrison Construction and United Utilities. In addition to organising the financial control of the project, the companies worked in partnership as construction contractor.

All the data was collected from the main Treatment Plant near Hatton (see Figure 3.4), outside Arbroath mainly due to the timing but most importantly because it provided the widest range of concrete pours. The Treatment Plant involved several very large circular settlement tanks, which due to the nature of the structure had to be poured continuously producing some very good data.
The concrete was solely supplied by a local company based eight miles from the site on the outskirts of Dundee. The concrete supplier offered the contractor a service that was second to none. Due to the size of the batching plant, which was relatively small, the supplier committed almost all of his resources to the Tay Wastewater Treatment Works project, which would have been a very favourable contract to attain for both parties. As it was the same personnel delivering the concrete throughout the project site familiarity was not an issue and evidently working relationships grew between the drivers and the concrete placing team on site.

Figure 3.3: Map showing the location of the Hatton wastewater and sludge treatment plant site and location of the batching plant used (Multimap, 2005)
3.1.3 Aberdeen Wastewater Treatment Works

The next project visited was the Aberdeen Wastewater Treatment Works project in 2000. Due to the close proximity to the Tay Wastewater Treatment Works project data was collected simultaneously. The project involved the design, build, operate and maintenance of four wastewater treatment plants in the North-West of Scotland. These plants were designed to serve 250,000 customers in Aberdeen, Stonehaven, Peterhead and Fraserburgh under a 30-year concession.

The financing of this £80 million project was organised under the UK government’s Private Finance Initiative (PFI). A concession company was formed for this project under the alias of Aberdeen Environmental Services Ltd. This company consisted of Balfour Beatty Plc, Kelda Group and Tyco Tech Ltd. The main contractor in the project was Balfour Beatty Construction (construction contractor) and Earth Tech (geotechnical engineering contractor).

This project had many similarities to the Tay Wastewater Treatment Works project. The site layout and structural detail were similar, however, it was invaluable to the success of this...
research project because it offered the investigator an opportunity to closely monitor different contractors approaches to similar projects.

As has been mentioned the project involved the construction of four wastewater treatment plants in Aberdeen (see Figure 3.5), Stonehaven, Peterhead and Fraserburgh. It was possible to collect data from three of the sites, with Stonehaven being the exception, as this leg of the project had not started when the investigator was collecting the data. These three sites produced an enormous amount of raw data and turned out to be an integral part of the overall study.

A large national concrete supplier supplied the concrete to all three of the sites. For all of them the batching plant was situated less than ten miles from the site. Another issue had to be dealt with for the Aberdeen leg of the project; the most obvious route from the batching plant to the construction site involved travelling through a large residential area of the city so restrictions were put in place and the delivery trucks had to make a three-mile diversion (see Figure 3.6). This made the delivery of the concrete extremely difficult to manage and increased the need for good relations between the supplier and contractor.

Figure 3.5: Map showing Aberdeen, Peterhead and Fraserburgh (Multimap, 2005)
3.1.4 *Falkirk Millennium Link Canal*

The next project studied was a very exciting £78m project restoring the Forth & Clyde and Union Canals to their former glory, linking the West and East coasts of Scotland with fully navigable waterways for the first time in over 35 years, see Figure 3.7. The Millennium Link was the biggest engineering project to be undertaken by British Waterways in Scotland. The project was funded by contributions from the Millennium Commission, Scottish Enterprise, the European Union, canal side local authorities and British Waterways.

The centrepiece of the Millennium Link Canal was the Falkirk Wheel, the world’s first rotating boat lift. The Falkirk Wheel is 115 feet (35 metres) high, the equivalent height of eight double-decker buses, and 115 feet (35 metres) wide and 100 feet (30 metres) long. The Wheel site takes up 110 acres (45 hectares), the bulk of which includes an abandoned open-cast mine, see Figure 3.8. The project involved major landscaping and the removal of 300,000 tonnes of soil.
This project offered a unique opportunity to study a piece of engineering history and supplied a very valuable data set. Construction materials included 7,000 cubic metres of concrete, 1,000 tonnes of reinforced steel, 1,200 tonnes of prefabricated steel and 35,000 square metres of canal lining. The concrete structures that were studied involved a wide variety of shapes and sizes. The main Falkirk Wheel site supplied much of the data. Due to the location of the site the ground conditions were quite often far from perfect. This introduced difficulties for the concrete delivery trucks which travelled from the local town of Falkirk, less than 5 miles away.

Figure 3.7: Map of Forth & Clyde and Union Canals

Figure 3.8: Falkirk Millennium Link Canal site showing the Falkirk Wheel
3.1.5 *Inverness Wastewater Treatment Works Project*

The final project studied was the Inverness Wastewater Treatment Works Project, Figures 3.9 and 3.10. Like the Tay project, the North of Scotland Water Authority entered into a contract with Catchment Ltd. The Inverness plant was part of a larger project, called the Highland Sewerage PFI, with the other plant being in Fort William.

The Inverness plant provided similar data to that collected at the Tay site, however it did give the investigator the opportunity to study how the same company undertakes a similar project. One major difference between the Tay and Inverness projects was the choice of concrete supplier. For the Inverness Wastewater Treatment Works Project Bardon Concrete Ltd supplied the concrete so comparisons could also be made between suppliers.

![Figure 3.9: Location of Inverness Wastewater Treatment Works](image)
Data collected from these 5 different projects formed the basis for the models that have been developed. The data is in the form of key times from the delivery and placement of the concrete and production rates achieved. Observing the operations from start to finish and timing the cycle times with a stopwatch collated these times. This form of data collection is known as work and method study from observation. In the case of the M6 Thelwall Viaduct, Falkirk Millennium Link Canal and Inverness Wastewater Treatment Works projects times were collated using historical record data and this method will also be discussed below. Table 3.1 shows the number of pours on each project and what data gathering method was used.
Table 3.1: Summary of the number of pours and data gathering method used

<table>
<thead>
<tr>
<th>Project</th>
<th>Year of completion</th>
<th>Location</th>
<th>Number of concrete pours observed</th>
<th>Method of Data Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6 Thelwall Viaduct</td>
<td>1994</td>
<td>Cheshire, England</td>
<td>64</td>
<td>Historical Records</td>
</tr>
<tr>
<td>Tay Wastewater Treatment Works</td>
<td>2000</td>
<td>Dundee, Scotland</td>
<td>54</td>
<td>From Observation</td>
</tr>
<tr>
<td>Aberdeen Wastewater Treatment Works</td>
<td>2000</td>
<td>Aberdeen, Scotland</td>
<td>175</td>
<td>From Observation</td>
</tr>
<tr>
<td>Falkirk Millennium Link Canal</td>
<td>2002</td>
<td>Falkirk, Scotland</td>
<td>23</td>
<td>Historical Records</td>
</tr>
<tr>
<td>Inverness Wastewater Treatment Works</td>
<td>2001</td>
<td>Inverness, Scotland</td>
<td>29</td>
<td>Historical Records</td>
</tr>
</tbody>
</table>

3.2 Work and Method Study

Harris and McCaffer (2001) state that experience suggests that 5 to 10% incremental improvements are attainable potentially in production efficiency through regular application of work study techniques, with the absolute amount diminishing each time gains are made on previous methods of working until the theoretical maximum is obtained, i.e. zero further gains. The process of observing, evaluating and improving performance in production operations called work study is defined in the British Standard Glossary of Terms (BS3138) as

A measurement service based on those techniques, particularly method study and work measurement, which are used in the examination of human work in all its contexts, and which lead to the systematic investigation of all the resources and factors which affect the efficiency and economy of the situation being reviewed, in order to effect improvement.

So in other words, method study is used to record work procedures, provide systems of analysis and develop improvements. Work measurement, usually thought of mutually with method study, and more commonly referred to as time study, is used extensively in this
research. It is the measurement of the time required to perform a task, e.g. position at pump and unload concrete, so that an output standard of production may be established. This can be quite often a worker as well as plant production rate. Such information is invaluable and often required in the estimating process and in this case used as part of the data in a method study so that actual production performance can be monitored against the standard expected.

Interestingly, BS 3138 does take the definition further by defining method study as

The systematic recording and critical examination of the factors and resources involved in existing and proposed ways of doing work, as a means of developing and applying easier and more effective methods and reducing costs.

Both these methods are fundamental to this research project and form the basis of the methodology used. By using these methods and adhering to the findings improvements are possible in the badly organised environment all too often found on UK construction projects. In particular, the method study technique should allow increased efficiency, increased productivity and a rise in competitiveness in concrete operations.

3.3 Data Gathered

Two different methods were used to collate the data used in this study, both of which used historical data as input (Smith, 2004). Historical data simply refers to the fact that the pours have already taken place and by using such data as the basis of the model it is assumed that the historical data will be representative of future pours. This assumption will be dependant on the source of the data and for this study a small percentage of the data has come from historical records, with the remainder coming from actual field observations. Both of these sources will be discussed and considered below.
3.3.1 Data from Historical Records

Records are kept in construction for a number of reasons, usually for control purposes. This may be for the control of finances, in which case records will be kept on material orders, deliveries etc. Records may also be kept for quality control such as testing results.

It is commonplace in the UK construction industry for records to be kept of all deliveries during concrete operations in the form of a "concrete pour record sheet". These contain pertinent data that can be used as input to a model. The concrete pour record sheet contains four key time components used in this study. The time the concrete was batched and arrival time on site gives the time to travel to site. The start time refers to the time that the concrete is first discharged into the hopper of the pump, and this time minus the arrival time gives the time the trucks have to wait in queue and position time. The final time component is the completion time, referring to when the concrete is fully discharged, this time minus the start time gives the total time to discharge the concrete. For each load that arrives on site the quantity of concrete in the truck is also recorded. Information is also given on the slump test and cubes taken from the mixes – this is of less interest to the modeller but is the main reason for the record sheet being kept.

- Advantages of using data from records are:
  - No extra work is required in gathering data
  - Large amounts of data can be collated from a wide range of projects and a wide range of dates

However, there are also disadvantages in using data from records and these are as follows:

- Data may not exist for processes under study
- Data may not be in the usable form
- It is difficult to assess whether data is actually representative of the real system, for example, it is quite often apparent that times are 'rounded' up to the nearest 5 minutes, affecting the accuracy of the data
- There may be gaps in the data
Whilst there appear to be more disadvantages than advantages with using data from records one must not underestimate the importance and value of having such data at hand. As long as it is used carefully and all due consideration is taken then it can be a very good foundation for any model.

3.3.2 *Data from Observation*

Data from records are useful if they exist; however, if specific data is required or as in this case a model is being developed data from observation is far superior. As can be seen from Table 3.1, the Tay Wastewater Treatment Works and Aberdeen Wastewater Treatment Works projects both consist of data from observation. This represents 65% of the total data set.

Advantages of using data from observation are:

- Data can be gathered in the exact form that it is required
- Data on specific factors can be included
- The observer will increase their 'knowledge' of the system under investigation
- The accuracy of the data is known, even if the modeller is not the data gatherer

Again, no method will be 100% perfect and even data from observation has a few disadvantages. These are:

- Extra time, effort and more importantly cost is need to collect data
- The act of observing the system may change the system and hence affect the data being collected

Data collection is a long process. Large amounts of time are needed to simply sit and observe operations, recording all the information necessary. The observer has to be well prepared and plan their task carefully as there is usually no opportunity to go back later to collect data that was missed. Software is available for data collection but the data on this
study was collected using a stopwatch and clipboard. Much debate has taken place recently about information sharing within the construction industry; however, this is not always the case when actually on UK construction sites. In most instances, especially in the early stages of being on site it can be difficult to gain the trust of the workers as they often see you as a mole and probably not without reason as you are continually monitoring their work.

3.3.3 Collection of Raw Data from Observation
As previously mentioned in section 3.3.2 the data collected from observation was collated using a stopwatch and clipboard. Essentially, the time to complete each task was recorded and used as the input to the models of the system and to provide a database for future work.

The method for collecting the data is as follows. The observer is situated at the loading area, usually far enough away from the concrete pump and operator and the placing team so as to be completely removed from the operations (this is as much do with the safety of the observer as avoiding interference of the operations), and able to see all arrivals and departures from the loading area clearly. The actual times recorded on site were the time the truck arrived on site, the time the truck started to discharge the concrete and the time it completed discharging the its load. The batching time was taken from the delivery receipt. Other factors that are recorded were the truck registration number, to enable the observer to calculate the cycle times of trucks, the quantity of concrete in each load. Recording the data on a sheet as that shown in Table 3.2 also allows the observer to make any remarks he feels appropriate. These may include periods of idleness caused by plant breakdown or occasions when the placing team are not ready for the concrete to be pumped into the formwork; such events may never be apparent when working with historical records. Table 3.2 also highlights a few other factors that may require further explanation.

- **Source** – this refers to the batching plant that the concrete has been delivered from. In large projects concrete may come from several batching plants.
- **Location** – this simply refers to the location on the construction site were the pour is taking place. It also gives an indication of what type of structure is being constructed.
• **Slump and Target Slump** – a slump test is carried out on each load of concrete that is delivered to site and determines the workability of the concrete. When ordering a batch of concrete from the supplier the contractor will specify a target slump, this will depend on the structure that is being erected, and state a range that the concrete slump must fall within.

• **Weather** – the weather is an extremely important factor in concrete operations. We assume that as the concrete pours being observed are taking place that the weather is not affecting whether or not a pour can actually take place, but it may affect the performance of the placing team and more obviously will have an effect on the ground conditions on site. During periods of persistent rain delivery trucks may find it difficult to actually manoeuvre on site.
Once the required time components are observed and recorded it is necessary to calculate the three key times; these are the interarrival time, position time and pump time. It is then possible to calculate the truck wait time, load pump rate, operation inactive time (pump idle time), and truck cycle time and finally the operation production rate. All of these can be calculated by hand but due to the amount of data being gathered an Excel spreadsheet was developed to speed up the process. A summary sheet was then developed for all pours to allow easy comparisons. Figure 3.11 shows a typical results summary sheet for the operations from the Tay Wastewater project.

<table>
<thead>
<tr>
<th>Source</th>
<th>Truck</th>
<th>Time</th>
<th>Quantity</th>
<th>Slump</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reg No.</td>
<td>Batch</td>
<td>Arrive</td>
<td>Start</td>
<td>Complete</td>
<td>Batch</td>
</tr>
</tbody>
</table>

Table 3.2: Concrete Pour Record used for the collection of data
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Trucks on Job</td>
<td>3</td>
</tr>
<tr>
<td>Concrete Mix C35A/20 Pfac Pump</td>
<td></td>
</tr>
<tr>
<td>Pour date 15-Jun-00</td>
<td></td>
</tr>
<tr>
<td>Location Baff Gallery Wall</td>
<td></td>
</tr>
<tr>
<td>Min Slump</td>
<td>40 mm</td>
</tr>
<tr>
<td>Max Slump</td>
<td>110 mm</td>
</tr>
<tr>
<td>Average Truck volume</td>
<td>8.00 m³</td>
</tr>
<tr>
<td>Cumulative Volume</td>
<td>64 m³</td>
</tr>
<tr>
<td>Total truck wait time</td>
<td>720 s</td>
</tr>
<tr>
<td>Total position</td>
<td>4020 s</td>
</tr>
<tr>
<td>Total pump</td>
<td>13680 s</td>
</tr>
<tr>
<td>Total inactive time</td>
<td>1860 s</td>
</tr>
<tr>
<td>Average Interarrival</td>
<td>2520 s</td>
</tr>
<tr>
<td>Average Wait</td>
<td>240 s</td>
</tr>
<tr>
<td>Average Position</td>
<td>540 s</td>
</tr>
<tr>
<td>Average Pump</td>
<td>1680 s</td>
</tr>
<tr>
<td>Average Slump</td>
<td>94.375 mm</td>
</tr>
<tr>
<td>Number of Loads</td>
<td>8</td>
</tr>
<tr>
<td>Number of Acceptable Loads</td>
<td>8</td>
</tr>
<tr>
<td>Number of Rejected Loads</td>
<td>0</td>
</tr>
<tr>
<td>Average %age rejected</td>
<td>0</td>
</tr>
<tr>
<td>Total pump idle</td>
<td>00:31 hrs</td>
</tr>
<tr>
<td>Total truck idle time</td>
<td>00:12 hrs</td>
</tr>
<tr>
<td>Overall duration</td>
<td>06:04 hrs</td>
</tr>
<tr>
<td>Productivity</td>
<td>10.55 m³/hr</td>
</tr>
<tr>
<td>Modified Productivity (Idle Time)</td>
<td>11.53 m³/hr</td>
</tr>
<tr>
<td>Costs:</td>
<td></td>
</tr>
<tr>
<td>Cost to contractor £</td>
<td>3143.82</td>
</tr>
<tr>
<td>Rejected concrete cost £</td>
<td>0.00</td>
</tr>
<tr>
<td>Hidden cost of idle trucks £</td>
<td>4.49</td>
</tr>
<tr>
<td>Hidden cost of idle pump £</td>
<td>47.00</td>
</tr>
</tbody>
</table>

Figure 3.11: A Typical Observations Results Summary Sheet
One addition to the summary sheet that has not previously been discussed is the costs involved in concrete operations. Table 3.3 shows the cost breakdown used to calculate the costs involved. All of these are taken directly from a leading contractors estimating department. Obviously the cost of a concrete pour is directly related to the quantity of concrete in that pour, however, plant and labour also have to be included. The contractor will have to pay for the placing team, concrete pump operator and is accountable for the hire of the pump and delivery trucks.

Some costs that the contractor will not tolerate, and in fact may not even be aware of, are the costs of pump and truck idleness. The contractor will be penalised for delivery trucks, for whatever reason, being delayed on site. In some instances this may be due to inefficient delivery of concrete but it is largely due to the placing team not being ready to receive the concrete or plant breakdown. Another cost that the contractor will be accountable for is the cost of the placing team and plant being idle, because they will obviously require payment regardless of their status. Usually due to poor delivery and communication between the contractor and supplier this cost can be extremely high.
<table>
<thead>
<tr>
<th>Costs Involved on Typical UK Concrete Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Costs</strong></td>
</tr>
<tr>
<td><strong>Plant (£/hour):</strong></td>
</tr>
<tr>
<td>Concrete Pump: 20.08</td>
</tr>
<tr>
<td>6m³ Mixer Truck: 20.54</td>
</tr>
<tr>
<td>8m³ Mixer Truck: 22.46</td>
</tr>
<tr>
<td>Poker Unit: 0.89</td>
</tr>
<tr>
<td><strong>Labour (£/hour):</strong></td>
</tr>
<tr>
<td>Concrete Ganger: 9.66</td>
</tr>
<tr>
<td>Concrete Placer: 7.15</td>
</tr>
<tr>
<td>Gen. Labourer: 6.82</td>
</tr>
<tr>
<td>Plant Operator: 9.16</td>
</tr>
<tr>
<td><strong>Material (£/m³):</strong></td>
</tr>
<tr>
<td>C7.5: 30.30</td>
</tr>
<tr>
<td>ST1: 33.60</td>
</tr>
<tr>
<td>C20: 34.70</td>
</tr>
<tr>
<td>ST4: 36.50</td>
</tr>
<tr>
<td>C25: 36.00</td>
</tr>
<tr>
<td>C30: 36.90</td>
</tr>
<tr>
<td>C35A/10, PFA: 43.80</td>
</tr>
<tr>
<td>C35A, PFA: 39.00</td>
</tr>
<tr>
<td>C40, PC: 48.45</td>
</tr>
<tr>
<td><strong>Extra Charges (£):</strong></td>
</tr>
<tr>
<td>Over for pump mix: 1.50</td>
</tr>
<tr>
<td>Superplasticiser on C35/10A: 3.60</td>
</tr>
<tr>
<td>Saturday Afternoon: 250.00</td>
</tr>
<tr>
<td>Sunday: 450.00</td>
</tr>
</tbody>
</table>
3.4 The Concept of Productivity

Improving productivity is a major concern of any profit-making organisation and there is an abundance of such organisations in the construction industry. The effective and efficient conversion of resources into marketable products determines the overall profits attained in this and any other industry. For this very reason, considerable effort has to be expended in order to firstly understand the concept of productivity and secondly to develop approaches, which shall increase productivity levels, ultimately making the construction industry more competitive. Due to the large increase in research being carried out in this area there are many definitions, applications and measurements being touted. The Concise Oxford Dictionary (9th edn) defines productivity as

The capacity to produce, the state of being productive; effectiveness of productive effort, especially in industry; production per unit of effort.

Perhaps not the most helpful definition as produce, productive and production are all used in the description, however, it does highlight some more interesting points. It states that there must be a capacity to produce or to do work and that this must be effective, and finally shows that productivity can be measured by the production per unit of effort (or rate) to measure output of the factors of production over a defined period of time.
3.4.1 Measuring Productivity in Concrete Operations

Productivity can also be very difficult to define in many construction operations and is not the same performance, however, two performance measures have already been talked about: effectiveness and efficiency. Both are often thought of together but have completely different meanings, with effectiveness measuring whether goals such as profits are met and whether the approaches, methods and tools used are correct, while efficiency is a direct measure of productivity. In engineering situations both can be thought to be output divided by input. For many construction operations both the input and output can be extremely difficult to quantify, however, both the output and input for concrete operations are relatively simple to quantify in physical terms.

The output in concrete operations is simply the amount of concrete required, and delivered, to complete a pour and is measured in cubic metres (m$^3$). The input is a little more difficult to calculate and requires careful assumptions and consideration. The input is usually taken as a factor of time and in this case shall be taken as the total pour duration, but first a few discrepancies within construction research must be addressed.

If we look at data taken from the Aberdeen Wastewater Treatment Works project (Figure 3.12), we can see that the pour realistically has three different start times – when the first load is batched, when it arrives on site and when the concrete is first discharged into the hopper of the pump. These will all give a different value for the total pour duration ranging from 3 hours 28 minutes to 3 hours 1 minute. So which one has been used? For this study the pour is assumed to start the instance the first load of concrete is batched, because once the first truck has been loaded the contractor is effectively hiring that piece of plant. Also, there are many things that could delay the truck on route to site and this will ultimately lengthen the pour duration and leave the placing team idle awaiting the delivery of the first load.

Finally, again considering Figure 3.12, it is possible to calculate the overall productivity for the presented concrete pour. The output can be seen to be 48 m$^3$ and the total pour duration
is 3 hours 28 minutes, therefore, the overall pour productivity can be calculated to be 13.85 m$^3$/hr.

<table>
<thead>
<tr>
<th>Pour Date:</th>
<th>03-Aug-00</th>
<th>Weather:</th>
<th>Cloudy/Warm</th>
<th>Target Slump:</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location:</td>
<td>Digester Tank Wall Pour 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source</td>
<td>Tullos</td>
<td>Batch</td>
<td>Arrive</td>
<td>Start</td>
<td>Complete</td>
</tr>
<tr>
<td>K568</td>
<td>16:22</td>
<td>16:45</td>
<td>16:49</td>
<td>17:20</td>
<td>8</td>
</tr>
<tr>
<td>K648</td>
<td>16:55</td>
<td>17:25</td>
<td>17:27</td>
<td>17:45</td>
<td>8</td>
</tr>
<tr>
<td>K568</td>
<td>17:45</td>
<td>18:00</td>
<td>18:05</td>
<td>18:25</td>
<td>8</td>
</tr>
<tr>
<td>K648</td>
<td>18:16</td>
<td>18:35</td>
<td>18:37</td>
<td>18:55</td>
<td>8</td>
</tr>
<tr>
<td>N6</td>
<td>18:37</td>
<td>18:56</td>
<td>19:00</td>
<td>19:35</td>
<td>8</td>
</tr>
<tr>
<td>K568</td>
<td>18:52</td>
<td>19:15</td>
<td>19:35</td>
<td>19:50</td>
<td>8</td>
</tr>
</tbody>
</table>

*Figure 3.12: Section of data taken from the Aberdeen Wastewater Treatment Works project*

### 3.5 Trends in Construction Productivity

Since the realisation that output has to be increased in the UK construction industry in order to compete globally both the government and construction firms have increased interest in this area. For example the Latham review suggested that productivity improvements in the UK construction industry of up to 30% were necessary to face the challenges of the next millennium (Latham, 1994). Egan (1998) added to this building on Latham's earlier work and suggested that productivity be increased by 10% per year. At the time of this report productivity was increasing by an average of 5% per year with the best projects demonstrating increases of up to 15% (Egan, 1998). These figures reflect the current improvements in the UK construction industry today, though there is much room for further improvements.

Similarly in the USA a series of reports has been published by Business Roundtable Publications based on a comprehensive study carried out to address declining US productivity through a Construction Industry Cost Effectiveness Project. Interestingly, in 1982, *The Business Roundtable's "Measuring Productivity in Construction"* summarized the challenges of quantifying construction productivity:
Unfortunately, construction productivity data for nation-wide use is not available. Moreover, a single measure of productivity, even if accurate, is insufficient for such a diversified industry as construction. (The Business Round-table, 1982)

To this date, 20 years later, the construction industry has not made any substantive movement in the accurate quantification of productivity, that is, in a manner applicable or useful throughout the industry.

3.6 Factors Influencing Productivity Rates in Concrete Operations

It has already been highlighted that productivity is not only very hard to measure, define and apply within the construction industry, but also to compare on-site productivity due to the large amount of influencing factors with no particular limit – in other words, everything affects productivity. Since the factors within concrete operations are very rarely constant and may vary from project to project and even in some instances within the same project almost anything can affect productivity. These factors are difficult not only to identify but also to control and Figure 3.13 shows how they affect the system. As the list is exhaustive only the key factors will be discussed here.

![Diagram](image)

**Figure 3.13:** Schematic diagram of the effects that unknown factors have on the concreting placing process

3.6.1 Weather

Being an outdoor industry, construction projects experience the whole range of climatic conditions, and this ultimately affects the performance of not only the labour but also the
plant. The UK climate tends, on average, to be cold and wet and this is inclined to be less conductive to mental and physical energy. A lot of research has been carried out in this area with Baldwin and Monthei (1971) ranking weather highest in causes of construction delays in the US. Harris (1979) also carried out his Ph.D. research on this topic and developed a model to evaluate effects of weather on construction projects in the UK to help avert the negative effect of the British climate on the country’s construction productivity.

3.6.2 Type of Structure
The construction industry deals with a very wide range of projects and this presents an ever-changing concrete pour. Concrete pours can be split into three main types: wall, column or base, and these all produce unique methods in which to carry them out. It is often impossible to develop one methodology that will deal with each type of concrete pour. Wall and column pours can be difficult to execute due to their very composition, and require skill and patience. Often the speed at which the concrete is placed must be controlled in order to avoid sagging and hence large amounts of rework. Base pours rely on a very quick and steady supply of concrete and this also can be difficult to achieve.

3.6.3 Role of Management
With the noted increase in project size and complexity and the rise in work sub-contracted out, the responsibilities at management level have become even more important. Management are responsible for employing, training and equipping workers to carry out a specific job in order to achieve maximum productivity. As with any industry it is apparent that managers are very quick to accepted praise for meeting goals but when things go wrong they too often lay the blame with their workers.

In concrete operations, and any other operation in a construction project, it is necessary for management to provide a link between themselves and the workers. Good management provides regular sessions were everyone has a chance to voice their opinion and discuss potential problem areas before they arise. Bad management results in low labour morale and increased absenteeism amongst other things, with management still demanding the same production levels from their workers.
With the idea of tapping into greater skill and knowledge there has been an increase in the use of subcontractors in concrete operations and this has changed the approach management have had to take. It was always the case that site agents and foremen were able to squeeze that extra bit of effort out of their own workers to increase productivity and meet deadlines, however this will prove more difficult with an outside company's workers.

3.6.4 Labour Organisation
Labour is recognised as one of the controlling variables in construction productivity and the two main forces behind a successful labour force is motivation and skill. Motivation depends on many factors such as a good working relationship with management and other trade workers, good wages and benefits and working conditions. Job sites with flexible work rules also promise productivity benefits.

The skill of the concrete placing team will depend on their qualifications, training and experience and their physical and mental ability. Although concrete placing can primarily appear to consist of nothing more than hard physical exertion, the skill comes only through proper training and experience.

3.6.5 Technology
Clearly productivity will improve with the use of the most effective plant and tools; for example, placing concrete with a pump will produce a higher productivity than with a wheelbarrow, however, it may not always be possible to use the latest in technological advances. The quantity of concrete placed in any given time may well increase when using machines but that does not necessarily mean that the quality will. This brings the issue back to proper training, so unless personnel have the adequate training to use new technology increases in productivity will not be maximised.
3.7 Summary of Dataset for this study

The data used in this research has been collected from five different projects, with a total of 345 pumped concrete pours. The data collected include:

- Type of pour (e.g. slab and base or column and wall)
- Overall pour duration between dispatch of first truckmixer and departure of final truckmixer from site
- Pump idle time
- Truckmixer idle time on site
- Interarrival time between trucks arriving
- Time taken for each truckmixer to position itself at the concrete pump
- Time to discharge concrete
- Number of truckmixers used for each pour

The data collected is summarised in Table 3.4 and the distributions of pour size and duration are given in Figures 3.14 and 3.15.
### Table 3.4: Numbers and types of pour, size and durations

<table>
<thead>
<tr>
<th>Project</th>
<th>No of Pours</th>
<th>Pour size (m³)</th>
<th>Overall duration (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>UQ</td>
<td>M</td>
</tr>
<tr>
<td>Inverness BS</td>
<td>15</td>
<td>33.00</td>
<td>26.40</td>
</tr>
<tr>
<td>Inverness CW</td>
<td>14</td>
<td>21.60</td>
<td>16.00</td>
</tr>
<tr>
<td>Aberdeen BS</td>
<td>61</td>
<td>160.00</td>
<td>120.46</td>
</tr>
<tr>
<td>Aberdeen CW</td>
<td>114</td>
<td>61.75</td>
<td>45.17</td>
</tr>
<tr>
<td>Dundee BS</td>
<td>22</td>
<td>172.5</td>
<td>146.55</td>
</tr>
<tr>
<td>Dundee CW</td>
<td>32</td>
<td>37.50</td>
<td>38.11</td>
</tr>
<tr>
<td>Falkirk BS</td>
<td>16</td>
<td>81.00</td>
<td>69.06</td>
</tr>
<tr>
<td>Falkirk CW</td>
<td>7</td>
<td>117.00</td>
<td>82.29</td>
</tr>
<tr>
<td>M6 BS</td>
<td>59</td>
<td>262.50</td>
<td>190.99</td>
</tr>
<tr>
<td>M6 CW</td>
<td>5</td>
<td>72.00</td>
<td>56.60</td>
</tr>
<tr>
<td>All projects BS</td>
<td>173</td>
<td>194.5</td>
<td>134.92</td>
</tr>
<tr>
<td>All projects CW</td>
<td>172</td>
<td>58.38</td>
<td>43.35</td>
</tr>
<tr>
<td>All Projects BS and CW</td>
<td>345</td>
<td>128.00</td>
<td>89.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BS</th>
<th>M</th>
<th>LQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

UQ = Upper Quartile  
LQ = Lower Quartile  
M = Mean  
BS = Base and Slab  
CW = Column and Wall
Figure 3.14: The Distribution of Pour Sizes in the Sample

(a) Column and Wall Pours

(b) Base and Slab Pours

Figure 3.14: The Distribution of Pour Sizes in the Sample
Figure 3.14: The Distribution of Pour Sizes in the Sample

(c) All Pours
Figure 3.15: The Distribution of Pour Durations in the Sample

(a) Column and Wall Pours

(b) Base and Slab Pours
The average pour size in the sample of 345 column and wall and base and slab pours was 90 $m^3$. In the sample one quarter of the pours were greater than 128$m^3$ and one quarter was less than 30$m^3$. This represents a very good spread of pumped concrete pours and should allow very good analysis of the data.

Table 3.5 highlights the extent of pump and truckmixer idle time during each concrete pour. On average for both column and wall and base and slab pours the pump idle time is seen to be approximately 15% of the overall pour duration and when we look at the two types of pours individually this appears to be a fairly consistent figure. Truckmixer idle time presents a more interesting variation.

To recap, truckmixer idle time is the time spent on site that a truckmixer is not adding value to the overall process. This mainly takes the form of queuing when the concrete pump is busy servicing other truckmixers or in extreme events when the pump is broken down or the placing team are not ready. As can be seen from Table 3.5, the idle time of truckmixers is very high and can often exceed 50% of the total pour duration. It is expected that this figure will vary from project to project as different contractors have different views of how concrete pours should be managed. By ensuring that a plentiful supply of concrete is available then pump idle time should be minimised and the concrete should be placed more efficiently. However, is this really the case?
Firstly, a comparison should be made of the truckmixer idle time during controlled and non-controlled pours. It can be seen from Table 3.5 that, indeed, truckmixer idle time as a percentage of the total pour time is greater in all five studied projects for non-controlled base and slab pours. In many cases this idle time is significantly higher and this is reflected in the averages for all projects. The truckmixer idle time during all base pours was found to be 35% of the pour duration compared to 14% of the pour duration for controlled column and wall pours.

In conclusion, considering again the pump idle times, there is little evidence that those pours with a plentiful supply of concrete truckmixers are significantly minimising the pump idle time.
<table>
<thead>
<tr>
<th>Project</th>
<th>No of Pours</th>
<th>Average Pour size (m²)</th>
<th>Average Overall duration (hr)</th>
<th>Pump Idle Time (hr) UQ</th>
<th>Pump Idle Time (hr) M</th>
<th>Pump Idle Time (hr) LQ</th>
<th>% of pour duration UQ</th>
<th>% of pour duration M</th>
<th>% of pour duration LQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverness BS</td>
<td>15</td>
<td>26.40</td>
<td>3.51</td>
<td>1.43</td>
<td>0.92</td>
<td>0.28</td>
<td>22.90</td>
<td>0.65</td>
<td>0.36</td>
</tr>
<tr>
<td>Inverness CW</td>
<td>14</td>
<td>16.00</td>
<td>2.52</td>
<td>0.65</td>
<td>0.36</td>
<td>0.00</td>
<td>12.86</td>
<td>0.34</td>
<td>0.23</td>
</tr>
<tr>
<td>Aberdeen BS</td>
<td>61</td>
<td>120.46</td>
<td>5.62</td>
<td>1.27</td>
<td>0.85</td>
<td>0.37</td>
<td>16.27</td>
<td>1.58</td>
<td>1.28</td>
</tr>
<tr>
<td>Aberdeen CW</td>
<td>114</td>
<td>45.17</td>
<td>4.05</td>
<td>1.27</td>
<td>0.85</td>
<td>0.42</td>
<td>20.04</td>
<td>0.35</td>
<td>0.27</td>
</tr>
<tr>
<td>Dundee BS</td>
<td>22</td>
<td>146.55</td>
<td>7.06</td>
<td>1.17</td>
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<td>0.00</td>
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<td>5.00</td>
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<td>2.03</td>
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<tr>
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<td>0.12</td>
<td>10.72</td>
<td>2.85</td>
<td>2.41</td>
</tr>
<tr>
<td>Falkirk CW</td>
<td>7</td>
<td>82.29</td>
<td>5.60</td>
<td>0.86</td>
<td>0.50</td>
<td>0.04</td>
<td>8.08</td>
<td>4.54</td>
<td>2.98</td>
</tr>
<tr>
<td>M6 BS</td>
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<td>190.99</td>
<td>6.59</td>
<td>1.17</td>
<td>0.81</td>
<td>0.33</td>
<td>11.56</td>
<td>3.79</td>
<td>3.15</td>
</tr>
<tr>
<td>M6 CW</td>
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<td>56.60</td>
<td>3.83</td>
<td>0.52</td>
<td>0.39</td>
<td>0.18</td>
<td>9.67</td>
<td>1.08</td>
<td>1.02</td>
</tr>
<tr>
<td>All projects BS</td>
<td>173</td>
<td>134.92</td>
<td>5.85</td>
<td>1.18</td>
<td>0.83</td>
<td>0.33</td>
<td>14.41</td>
<td>3.17</td>
<td>2.24</td>
</tr>
<tr>
<td>All projects CW</td>
<td>172</td>
<td>43.35</td>
<td>4.01</td>
<td>1.08</td>
<td>0.70</td>
<td>0.23</td>
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<td>0.62</td>
</tr>
<tr>
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<td>0.77</td>
<td>0.30</td>
<td>15.61</td>
<td>2.03</td>
<td>1.43</td>
</tr>
</tbody>
</table>

UQ = Upper Quartile  
LQ = Lower Quartile  
M = Mean  
BS = Base and Slab  
CW = Column and Wall
So far the focus has been on the percentage of idle time and waste incorporated in the concrete placing and delivery cycle, next it may be worthwhile to study the integral parts of the cycle. Table 3.6 shows the breakdown of the time spent on site by the truckmixer.

Table 3.6: Observations of truckmixer usage of time on site

<table>
<thead>
<tr>
<th>Project</th>
<th>No of Pours</th>
<th>Average Pour size (m³)</th>
<th>Average Overall duration (hr)</th>
<th>Average Interrarrival Time (mins)</th>
<th>Average Wait Time (mins)</th>
<th>Average Position Time (mins)</th>
<th>Average Pump Time (mins)</th>
<th>Average Wash Out Time (mins)</th>
<th>% of total pour duration</th>
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<tr>
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<td>15</td>
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</tr>
<tr>
<td>Inverness CW</td>
<td>14</td>
<td>16</td>
<td>2.52</td>
<td>36.46</td>
<td>8.36</td>
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<td>22.02</td>
<td>10.34</td>
<td>17.38</td>
</tr>
<tr>
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<td>9.15</td>
<td>15.31</td>
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<td>14.33</td>
<td>22.46</td>
<td>5.38</td>
<td>54.9</td>
</tr>
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<td>7.06</td>
<td>22.95</td>
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<td>7.77</td>
<td>14.73</td>
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<td>30.37</td>
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<td>10.45</td>
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<td>6.63</td>
<td>13.59</td>
<td>8.54</td>
<td>23.18</td>
</tr>
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<td>22.75</td>
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<td>7.37</td>
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<td>3.83</td>
<td>23.6</td>
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<td>9.8</td>
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<td>8.3</td>
<td>7.63</td>
<td>12.75</td>
<td>8.56</td>
<td>29.35</td>
</tr>
<tr>
<td>All projects</td>
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<td>43.35</td>
<td>4.01</td>
<td>37.56</td>
<td>10.46</td>
<td>13.24</td>
<td>22.86</td>
<td>7.67</td>
<td>25.57</td>
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<tr>
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<td>89.27</td>
<td>4.93</td>
<td>29.4</td>
<td>9.38</td>
<td>10.43</td>
<td>17.79</td>
<td>8.32</td>
<td>27.47</td>
</tr>
</tbody>
</table>

BS = Base and Slab  
CW = Column and Wall

3.8 Productivities being achieved

As discussed earlier productivity rates are universally used within the construction industry. They allow comparisons to be made within individual activities from project to project and
country to country. From the vast amount of data collected on the five sites a productivity study will allow an insight into how efficiently and effectively the concrete pours have been planned and managed.

Table 3.7 shows the productivities achieved on each site for both controlled and non-controlled concrete pours. It is useful to compare these rates with those obtained via other independent study and some comparable figures for pumping in the UK, West Germany and Hong Kong are available (Anson et al, 1989 and Anson and Wang, 1998). The UK based study had a mean pour size of 92 m³ and a placing speed of 15.5 m³/hr, the West German study had a mean pour size of 170 m³ and a placing speed of 20.5 m³/hr and the Hong Kong based study had a mean pour size of 144 m³ and a placing speed of 21.4 m³/hr. The UK sample numbered 70, the West German sample numbered 32 and the Hong Kong based sample numbered 51 pours. These rates range from 15.5 m³/hr to 21.4 m³/hr and therefore compare well with those found in this study which, as can be seen from Table 3.7, range from 7.9 m³/hr to 32.6 m³/hr with an average of 15.8 m³/hr. The UK rate from Anson et al’s studies compares very closely with this study but conclusions about which country’s industry is performing better should be made with care: there are many variations in types of pour, pour size and number of pours in the samples of all of these studies.
Table 3.7: Key performance parameters

<table>
<thead>
<tr>
<th>Project</th>
<th>No of Pours</th>
<th>Average Pour Size (m³)</th>
<th>Average Measured Overall Productivity (m³/hr)</th>
<th>Average Intrinsic Overall Productivity (m³/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>UQ</td>
<td>M</td>
</tr>
<tr>
<td>Inverness BS</td>
<td>15</td>
<td>26.40</td>
<td>8.79</td>
<td>8.02</td>
</tr>
<tr>
<td>Inverness CW</td>
<td>14</td>
<td>16.00</td>
<td>7.54</td>
<td>6.70</td>
</tr>
<tr>
<td>Aberdeen BS</td>
<td>61</td>
<td>120.46</td>
<td>24.40</td>
<td>19.04</td>
</tr>
<tr>
<td>Aberdeen CW</td>
<td>114</td>
<td>45.17</td>
<td>12.43</td>
<td>10.97</td>
</tr>
<tr>
<td>Dundee BS</td>
<td>22</td>
<td>146.55</td>
<td>24.72</td>
<td>20.70</td>
</tr>
<tr>
<td>Dundee CW</td>
<td>32</td>
<td>38.11</td>
<td>9.70</td>
<td>8.37</td>
</tr>
<tr>
<td>Falkirk BS</td>
<td>16</td>
<td>69.06</td>
<td>18.24</td>
<td>15.71</td>
</tr>
<tr>
<td>Falkirk CW</td>
<td>7</td>
<td>82.29</td>
<td>15.60</td>
<td>14.50</td>
</tr>
<tr>
<td>M6 BS</td>
<td>59</td>
<td>190.99</td>
<td>33.74</td>
<td>28.74</td>
</tr>
<tr>
<td>M6 CW</td>
<td>5</td>
<td>56.60</td>
<td>18.00</td>
<td>14.46</td>
</tr>
<tr>
<td>All projects BS</td>
<td>173</td>
<td>134.92</td>
<td>27.49</td>
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</tr>
<tr>
<td>All projects CW</td>
<td>172</td>
<td>43.35</td>
<td>12.37</td>
<td>10.38</td>
</tr>
<tr>
<td>All Projects BS and CW</td>
<td>345</td>
<td>89.27</td>
<td>21.82</td>
<td>15.84</td>
</tr>
</tbody>
</table>

UQ = Upper Quartile  
LQ = Lower Quartile  
M = Mean  
BS = Base and Slab  
CW = Column and Wall

The productivities achieved on the five sites under investigation vary significantly. The average for the 345 concrete pours studied with an average pour size of 89.27m³ was 15.84m³/hr. Of course due to the nature of the concrete pours it is advantageous to look at the controlled and non-controlled pours separately.
The average measured overall productivity for base and slab pours ranged from 8.02m³/hr – 28.74m³/hr revealing a large variation in what should be the easier type of pours to control and predict. The average measured productivity for base and slab pours was 21.27m³/hr. For the observed controlled column and wall pours the average measured overall productivity ranged from 6.70m³/hr to 14.50m³/hr. The average measured productivity for column and wall pours was 10.38m³/hr.

The range of productivities seen in Table 3.7 may be due to different management styles and quality of placing team and operative skills. The right hand column of Table 3.7 shows the performance which theoretically would have been achieved if there had been no interruptions to the supply of concrete and no other delays due to placing plant problems or poor pour preparation etc. Of course such ideal conditions can rarely occur, but it is interesting to note the difference between what is actually observed and what perfect organisation would achieve. Instead of placing at 15.84m³/hr, we would achieve 18.86m³/hr, an increase in the order of 20%.

3.9 Productivity in relation to pour size

Figure 3.16, for the 345 pours is a plot of productivity against size of pour. Three plots are shown: column and wall pours, base and slab pours and all pours. Although there is considerable scatter, a linear relationship can reasonably be said to exist. The line shown has been fitted by regression and thus describes, or models, the relationship in the UK between productivity being achieved and concrete pour size on construction sites.

[In chapter 5, regression analysis is used in more detail to model concrete placing and delivery.]
(a) Column and Wall Pours

Figure 3.16: The Relationship Between Productivity and Pour Size

(b) Base and Slab Pours

Figure 3.16: The Relationship Between Productivity and Pour Size
The Relationship Between Productivity and Pour Size

Table 3.8: Statistics for Figure 3.16

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>Coefficient of Determination</th>
<th>Volume Mean</th>
<th>Volume Standard Deviation</th>
<th>Productivity Mean</th>
<th>Productivity Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column and Wall</td>
<td>172</td>
<td>48.29%</td>
<td>43.35</td>
<td>23.42</td>
<td>10.38</td>
</tr>
<tr>
<td>Base and Slab</td>
<td>173</td>
<td>70.15%</td>
<td>134.92</td>
<td>89.20</td>
<td>21.27</td>
</tr>
<tr>
<td>All Pours</td>
<td>345</td>
<td>78.12%</td>
<td>89.27</td>
<td>79.70</td>
<td>15.84</td>
</tr>
</tbody>
</table>
3.10 Provision of concrete to site

A key factor promoting the productivity of a concrete pour is timely supply of ready mixed concrete to site. Ideally, an uninterrupted supply is required but the fact that a finite number of truckmixers is available to the industry as a whole and each plant is supplying various sites on any particular day makes an uninterrupted supply impossible to achieve in general. Variability in road traffic conditions and the fact that concrete must be reasonably fresh at the time of placing are also relevant factors.

Illustrating the difficulty, for only 36 of the 345 pours studied (approx. 10%), as stated above, was an uninterrupted supply of concrete achieved.

The measured average interruptions in the supply of concrete were 14.4%, 16.8% and 15.6% for pumped column and wall, base and slab and all pours combined respectively. Figure 3.17, gives the distribution of time spent waiting for concrete for all concrete pours in the sample.
Figure 3.17: Distribution of Periods on Site Waiting for Concrete Delivery

(a) Column and Wall Pours

(b) Base and Slab Pours
Although the measured average interruption in supply of concrete is approximately 16% meaning that truckmixers were present on site for only about 84% of pour time, the actual provision of truckmixer-hours, a different measure of the level of ready mixed concrete service, was generally much greater than the number of hours of pour duration. Figure 3.18 gives the distribution of truckmixer hours provision on site as a % of total pour time.
Figure 3.18: Distribution of Truckmixer Hours provision on Site

(a) Column and Wall Pours

(b) Base and Slab Pours
Figure 3.18: Distribution of Truckmixer Hours provision on Site

Figure 3.19 is a diagram showing for each pour the truckmixer hour provision on site, as a percentage of pour duration plotted against the interruption to concrete supply also as a percentage of pour duration. This graphically illustrates the difficulty being experienced in matching supply to requirement as discussed previously. This diagram is particularly interesting and useful because it neatly illustrates the matching performance actually being achieved. If we define an arbitrary zone showing a good match of supply to requirement as a truckmixer hour provision of between 100 and 150% of pour time and an interruption in supply of not more than 10% of pour time, as represented by the boxed area on Figure 3.19. As can be seen, only approximately 15% of operations fell into this ‘ideal zone’. A poor match is unhelpful to contractors when wait times are long and unhelpful to concrete suppliers when truckmixers are standing idle in queues on site, or perhaps even held up in traffic.
Figure 3.19: Relationship between Truckmixer Provision on site and percentage pour time without Concrete

Figure 3.19, in fact, shows the service sites are receiving from ready mixed concrete plants. The productivity of concreting ought to be enhanced, i.e. the productivity of placing on site and delivery by the supplier seen as a combination, if a much higher percentage of pours were to fall within the boxed 'ideal zone' in Figure 3.19. The site contractor is probably not overly concerned with high truckmixer provision; however, the concrete supplier is concerned with both of the service aspects of the diagram. Perhaps the concrete supplier, in order to uphold his reputation for reliability, chooses to over supply concrete in order to avoid excessive gaps?

What constitutes an 'excessive' gap will depend on several factors. The importance of the pour (which usually equates to the size of pour), the placing method and the degree of urgency as communicated by the site to the plant. Taking these into account, as well as the distance involved and likely traffic conditions and the other commitments for that day, a site will normally be assigned a specific number of truckmixers. When allocating resources the usual supplier objective is to maximise the happiness and provide confidence of the
intention to complete the work. When gaps start appearing in the delivery of the concrete this will immediately start affecting the satisfaction of the customers. The outcome of this intrinsically difficult allocation problem is illustrated in Figure 3.19.

3.11 Chapter Summary

This chapter is devoted to the data collected on real construction sites during this research project. The five projects studied were explained and the individuality of each highlighted. The dataset collated is one of the largest of its type, representing 400 individual concrete pours. The key findings of the chapter are highlighted below:

- Concrete pours are generally wall, column or base pours. Each of these has individual characteristics and requirements. Generally the concrete in column and wall pours will be placed at a slower rate than for base pours.

- The data for this study was gathered from both historical records, and actual field observations.

- During data collection on site the times recorded on site were the time the truck arrived on site, the time the truck started to discharge the concrete and the time it completed discharging the its load. This enabled the calculation of the three key times; these are the interarrival time, position time and pump time. As well as these key time events several other factors were noted, e.g. weather, type of pour, etc.

- The concept of productivity was introduced. Productivity studies are one of the most used methods of making performance comparisons in the construction industry. High productivity rates are fundamental to any successful task, however, these are not always easy to achieve. Many variables affect the productivity rate and many of these have been highlighted and discussed in this chapter.

- The productivities achieved on the five sites under investigation varied significantly. The average for the 345 concrete pours studied with an average pour size of 89.27m$^3$ was 15.84m$^3$/hr. The average measured productivity for base and slab pours was 21.27m$^3$/hr and the average measured productivity for column and wall pours was 10.38m$^3$/hr.
• The concept of waste, in the form of truckmixer and concrete pump idleness, was highlighted. For all concrete pours in the dataset, on average, truckmixers were idle for 25% of the total pour duration and the concrete pump was idle for 16% of the total pour duration. The cost associated with these delays is, of course, very difficult to determine but a very approximate estimate indicates that the cost of resources associated with these idle times come to some £23,500. This is just for the operations observed in this project, which of course constitute a small proportion of all operations for these projects.

• A key factor promoting the productivity of a concrete pour is timely supply of ready mixed concrete to site. Illustrating the difficulty, for only 36 of the 345 pours studied (approx. 10%), as stated above, was an uninterrupted supply of concrete achieved.

• Figure 3.19 shows a "cost effective zone" that all concrete pours should be striving to fall within. This in effect is an arbitrary zone showing a good match of supply to requirement as a truckmixer hour provision of between 100 and 150% of pour time and an interruption in supply of not more than 10% of pour time. For the pours studied only 15% of the 345 pours lie within this zone.
Chapter 4

A New Philosophy for a New Millennium

The first chapter dealing with trying to evaluate and investigate ways to make the concrete delivery and placement process more efficient. Lean construction is introduced and explained, with an attempt being made to apply many of its innate philosophies to concrete operations.
Chapter 4 A New Philosophy for a New Millennium

4.1 History of Lean Construction

In Chapter 2, Lean Construction was introduced as a potential methodology for investigating concrete placing operations. In this Chapter, the philosophy will be presented in a fuller and more critical manner to determine whether it is appropriate for this study. It us useful to first appreciate the history of LC and why it has been taken up by the industry.

Lean construction has been developed from management principles used by Toyota, who doggedly set about eliminating waste in the car manufacturing industry. The term 'lean' was coined by the research team working on international auto production to reflect both the waste reduction nature of the Toyota production system and to contrast it with craft and mass forms of production (Womack et al., 1991). Whilst lean production was successful in the car manufacturing industry, many believed that it would not be applicable in the dynamic world of construction. Nevertheless, subsequently a great deal of work has been carried out in this area with many favourable findings.

Lean construction advocates the elimination of waste whilst using fewer inputs. Howell (1999) states that moving towards zero waste – perfection – shifts the improvement from the activity to the delivery system. While much work has been carried out concerning particular activities, the delivery system is regularly being overlooked. Lean principles, such as 'Just-In-Time' (JIT) delivery has gone some way in addressing this issue. Tommelein and Li (1999) have been active in this area and have explained concepts underlying a just-in-time production system. A further 'lean' principle is the analysis of all operations as a series of flow and conversion activities (Koskela, 1992). Conversion activities are those operations performed in adding value to the material or information being transformed to a product. Flow processes represent activities such as inspection, moving and waiting. This is an ideal model on which to base the investigation of concrete operations.
4.2 Applying Lean Construction Principles to Concrete Operations

Concrete operations are littered with variables and uncertainties. Unless these are taken into account at the early planning stages many can result in wasteful activities, which are difficult to manage once construction has started. It may be possible to apply lean construction principles to identify and manage these uncertainties.

Firstly, consider the process at the concrete batching plant and construction site as a series of flow and conversions (see Figure 4.1). Conversion activities are those operations performed in adding value to the material or information being transformed to a product and are shown unshaded. Flow processes represent activities such as inspection, moving and waiting and are indicated in the shaded boxes. This method of analysis, adopted by Koskela (1992, 2000) is appropriate for concrete operations. It allows us to break down the process and easily identify all tasks and subprocesses that can potentially cause delays and material misuse, and thus waste. It is important that the practical application of whether the process can be adapted in this manner is explored.

Quite often, models are developed that only deal with conversion processes - these are activities that add value to the final product and it is reasonable to attempt to maximise them. Alternatively, it is possible to consider the flow processes which, whilst not always adding value, are an integral part of the overall operation. A revised modelling methodology could therefore attempt to maximise the output from conversion activities whilst also minimising the effects of flow processes (i.e. minimising waste). Methodologies such as JIT can greatly reduce the amount of waste involved in these flow processes by controlling the amount of moving and waiting involved in the operations.
4.3 Lean principles used to reduce waste in flow processes

With the advent of lean thinking in construction, many heuristic principles have evolved. Many of these are applicable to concrete operations and may well reduce and control the amount of waste that is present in flow processes. In his technical report, Koskela (1992) identified eleven principles that apply to the flow processes and its subprocesses. The following principles outlined by Koskela will be examined with particular reference to the flow and conversions in concrete operations, as shown in Figure 4.1:

1. Reduce the share of non value adding activities
2. Increase output value through systematic consideration of customer requirements
3. Reduce variability
4. Reduce the cycle time
5. Simplify by minimising the number of steps, parts and linkages
6. Increase output flexibility
7. Increase process transparency
8. Focus control on complete process
9. Build continuous improvement into the process
10. Balance flow improvement with conversion improvement
11. Benchmark

4.3.1 *Reduce the share of non value adding activities*

As discussed in the previous section, it is important to identify the main differences between value adding and non value adding activities.

- A value adding activity is an activity that converts material and/or information towards that which is required by the customer, e.g. travel to site, discharge of concrete.
- A non value adding activity (also called waste) is an activity that takes time, resources or space but does not add value, e.g. queuing.

These activities form the very basis of the flow and conversation model presented in Figure 4.1. The next task is to reduce the share of non value adding activities and in order to do this it is important to not only identify them but also to examine their root cause.

Most processes, whether it is in manufacturing or construction, show that non value adding activities are present. If they are present in the majority of processes, surely, they must have a place in the process or are we dealing with those activities that many have found impossible to eradicate?

In concrete operations, we have identified a number of value and non value adding activities; however it is critical that those non-value adding activities identified are just that – non value adding. In the model developed in Figure 4.1, many of those activities shown as non-value adding are an integral part of the overall process and thus must add value e.g. travel to and from site and travel on site.
Therefore, what is truly non-value adding in this example? Obviously neither the concrete supplier or the customer will benefit from idleness in the process or in the extreme case from rejected concrete, and if every other part of the process is working smoothly and efficiently these will have serious implications on the overall productivity. Koskelo (1992) suggests that the root causes for non-value adding being present in a process are: design, ignorance and the inherent nature of production. One of the questions of this chapter is whether these principles can be applied to concreting operations.

Non value adding activities exist by design in hierarchical organisations. In the placement of concrete, it is necessary for the task to be divided into subtasks executed by different specialists – concrete placing team (including pump and/or crane and skip operator), quality assurance engineer and concrete supplier – with this non value adding activities increase: inspecting, moving and waiting.

Lack of knowledge could also be another source of non-value adding activities. Concrete placing has been a fundamental task in construction for many years, but unfortunately the process has been allowed to evolve and develop in a makeshift manner. We could argue that technology has increased productivity yet not everything is being done to make the process a slick machine.

The final root cause for non value adding activities is by far the most worrying and disturbing – construction practitioners often cite waste as being an unfortunate, yet intrinsic, part of construction. Moreover, unfortunately all too often it is those with a lack of knowledge, and in a position to make changes, that make this statement. We can all accept that defects do emerge and accidents do happen, however, more must be done to improve the overall process and improve all parts of it.

Most of the principles discussed below discuss the suppression and elimination of non value adding activities.
4.3.2 Increase output value through systematic consideration of customer requirements

This is another fundamental principle. Value is ultimately generated through fulfilling customer requirements, not as an inherent merit of conversion. For each activity, there are two types of customers, the next activities and the final customer.

The final customer in concrete placing varies from project to project, however their requirements are the same. They require a predetermined amount of concrete to be placed without delay, at the time agreed, with no increase in costs.

If we look more closely at the overall process and the subprocesses we can see that "customers" within the process all have different requirements.

- The concrete delivery truck driver requires the concrete to be ready on time,
- The quality assurance engineer requires the concrete to be of an acceptable quality,
- The concrete pump operator and placing team require that they have a sufficient number of trucks, and therefore concrete, available so they have no delay in the placement of the concrete,
- The truck driver is then reliant on site logistics to ensure that he can make a safe and uninterrupted journey to the wash-out area and from site.

Only after all this takes place can the supplier then arrange for his truck to arrive to the dispatching depot to start the process all over again.

4.3.3 Reduce variability

This is one of the most critical steps that can be made in order to reduce waste and increase the performance levels of concrete operations.

The dynamic nature of concrete operations has led to research identifying a very large amount of variability (for example Anson and Wang, 1998 and Dunlop and Smith, 2000) and a major part of this study concerns the investigation of this problem. The author has used
data collected on civil engineering projects and, after identifying a number of measurable variables, carried out a regression analysis in order to reveal the most significant. A further discussion and summary of the findings of this study can be found in Chapter 5.

If variability can be predicted then variability can be managed. For example, it is clearly useful to have a prediction of total pour time. This enables the activity, and those surrounding it, to be planned adequately and make sure that an adequate amount of resources and materials are on hand.

4.3.4 Reduce the cycle time

If the conversion variables (for example concrete discharge time) are predicted and reduced then cycle time shall automatically be bettered. More significantly, perhaps, the cycle time can be improved even further by reducing waiting times, delays, moving times and inspection times, i.e. the flow processes.

Flow processes are easily thought of and measured in terms of time. Time is a more useful and universal metric than cost and quality because it can be used to drive improvements in both (Krupka, 1992). When measuring cycle time in concrete operations it includes the following: pumping time, inspection time, queuing time, wash-out time and transportation time from batching plant to site and back again. From all of these the only time that is strictly non-value adding is the queuing time. By using JIT objectives in the strictest of manners it is potentially possible to all but eliminate this, hence reducing the cycle time: in an ideal world it would be possible to plan operations such that one truck mixer finishes discharging its concrete just as the next is arriving on site, also assumes that the placing team can work continuously. In reality it is likely that this would be unachievable due to the stochastic nature of the process as has been previously discussed.

The other times in the cycle time equation are all necessary, however, all will inevitably have a certain degree of waste attached to them. For example, transportation to and from site is essential but will involve a lot of variability that end up causing waste if not addressed appropriately. The transportation time can be compressed by choosing batching plants closer to the site and making use of access roads at off peak times reducing the chance of excessive traffic congestion.
4.3.5  *Simplify by minimising the number of steps and parts*

It has previously been demonstrated that the concrete delivery and placing process is not a particularly complex one but one that is littered with uncertainty and waste. By its very nature, the number of steps and parts involved in the process is already perceived to be at a minimum. However, if we take into account that we are dealing with a process with two distinct cycles – batching plant and final location of the concrete – it may be possible to simplify these cycles and this will be attempted later in the Chapter.

Due to the amount of time spent travelling to and from the required site, it can be seen that the choice of dispatch plant is critical and that by ensuring that all potential plants are researched thoroughly travel time can be cut. At this stage consideration may also be given to the use of on-site batching plants, however, this will only be practical for large-scale projects involving large volumes of concrete.

Simplification can also come about through organisational changes. Multi-skilled, autonomous teams can greatly reduce non-value adding activities by constantly bettering performance.
4.3.6 Increase output flexibility
The increase of flexibility is one that may not be overly applicable to the process of concrete
delivery and placement. Output in the majority of cases is set and only through better
management of the cycle time and variability can this be improved.

Practical approaches to increased flexibility include (Stalk and Haut, 1990, Child et al. 1991):

- Minimizing lot sizes to closely match demand
- Reducing the difficulty of setups and changeover
- Customising as late in the process as possible
- Training a multi-skilled workforce

4.3.7 Increase process transparency
The concrete delivery and placement process is a cyclic process, which does not alter
significantly from project to project. A very important management tool is to make all steps
in any process transparent so that everyone involved in that process is accountable for their
actions. This allows the process to be directly observable through organisational or physical
means, measurements and in-house display of information. By doing this, it allows
continual control and improvement to take place.

4.3.8 Focus control on the whole process
There are two prerequisites for focusing control on complete processes. First, the whole
process has to be measured.

Secondly, there must be a controlling authority for the complete process. This responsibility
traditionally rests with the Project Manager for the Civil Work who has the task of not only
ensuring that concrete is delivered and placed efficiently and effectively but manages many
other elements on a particular project. A more practical solution is to put in place self-
directed teams who are responsible for liaising with the concrete supplier, ordering the
quantities required, testing the concrete and finally the placement itself. This is what
happens on many construction projects and it could be argued that this particular tenet of
LC is implemented by rote
4.3.9  **Build continuous improvement into the process**
The effort to reduce waste and to increase value is an in-house, incremental, and repetitive activity that must be carried out continuously. In order to achieve long term improvements in the concrete delivery and placement process several ideas and concepts must be put in place

- Better measurement and monitoring of improvements
- Setting targets (e.g. elimination of idleness and cycle time reduction), by means of which problems are unearthed and their solutions sought
- Giving responsibility for improvement to all involved in the process
- Better understanding of procedures of best practice, to be constantly challenged by better ways

This list is by no means exhaustive. Continuous improvement is vital to the improvement of many construction processes and must be done in small steps, fine-tuning until greater efficiency is achieved. The goal is to eliminate the root of the problems rather than cope with their effects.

4.3.10  **Balance flow improvement with conversion improvement**
What must be considered firstly is the question of whether a process is automatically improved if non value adding activities are improved (i.e. reduced). In theory, the answer to this question is yes, however, there is a fine line between both flow and conversion and in order to improve both a balance must be met.

In a situation where flows have been neglected for many years, the potential for flow improvement is usually higher than conversion improvement. On the other hand, flow improvement can be started with smaller investments, but will usually require a longer period than a conversion improvement.

The crucial issue is that flow improvement and conversion improvement are intimately interconnected.
4.3.11 Benchmark

Benchmarking is used extensively in manufacturing and increasingly has been used as a tool in the construction industry. It allows comparison between different companies and countries and if used carefully can greatly benefit those prepared to invest and work to become world class.

For many years the UK construction industry has lagged behind countries such as Germany, USA and Hong Kong in the placement of concrete (Wang and Anson, 2000 and Proverbs et al, 1999). Whilst the other countries have strived to compete and excel, the UK has fallen behind and only now is realising that there are massive savings to be made not only in concrete placing but other processes in the construction industry. Through extensive research, data and improved methodologies are readily available.

The basic steps of benchmarking include the following (Camp, 1989):

- Knowing the process and assessing the strengths and weaknesses of subprocesses
- Knowing the industry leaders or competitors and finding, understanding and comparing the best practices
- Incorporating the best and copying, modifying or incorporating the best practices in your own subprocesses
- Gaining superiority by combining existing strengths and the best external practices.
4.4 Quality approach vs. time based management

The eleven principles for flow process design and improvement suggested by Koskela (1992) and discussed above all lead towards continuous improvement and the belief that by sharing information and making all processes and subprocesses transparent non value adding activities can be reduced. Continuous improvement is yet another concept that has been subjected to rigorous research (Imai, 1986), however it is closely associated with both quality control and time based management.

If we consider both the quality approach and time based management we can see that they have very different core objectives, however both are intrinsically connected. Importantly, both are central to the development of an improved approach to many construction processes.

The quality approach has variability as its core principle whilst time based management endeavours to reduce cycle times. Variability in the flow of work often extends the cycle time and reduces system throughput by increasing the amount of waste in a process. If we are to successfully achieve reductions of cycle time and eliminate waste then applying lean principles to understand and reduce the variability in concrete operations is the next obvious step.

4.5 Variability and Waste

Variability, while common even to well-run construction projects, is generally believed to impede performance. Variability can induce fluctuating and unexpected conditions, making objectives unstable and obscuring the means to achieve them. Poor management can promote unnecessary changeability in construction conditions that leads to variable performance. Variability in performance can also be due to the nature of a project and to the limitations of management to predict and develop efficient countermeasures.

In lean thinking, variability in the flow of work through construction processes is treated as impeding system performance. Recent proponents of lean construction have focused on
workflow (output) variability to improve project performance. For example, the Last Planner Technique developed by Ballard and Howell (1994).

At this process level, variability pertains to:

1. **Scope of work**: What work is to be performed is not necessarily stated clearly in contract documents. An inadequate definition of the scope of work to be undertaken causes many issues in subcontract coordination. In addition, a contract’s scope may change during construction to accommodate a client changing their mind, to correct design mistakes, to deal with unforeseen site conditions, etc.

2. **Duration and timing**: Duration gauges the amount of time elapsed from start to finish of an activity. These probabilistic though measurable quantities provide a way in which to summarise what goes on during construction, and also describe how successor activities may be affected when the timing and durations of their predecessors are uncertain.

3. **Quantity**: Variation in quantity results from using imprecise design quantities and estimating rules that result in procuring and transporting quantities that differ from required quantities. Also, encountering site conditions, and worker skill levels that were not anticipated in advance but that result in the consumption of materials at a rate different from what was anticipated, changing work to be done, etc. These practices are bound to lead to difficulties in estimating quantities.

4. **Quality**: Variation in quality may be the result of activities being executed by workers with varying skill levels, using different methods and subject to changing environmental conditions, etc. Inspection and testing will determine which variation in quality is acceptable and whether or not rework will be necessary.

5. **Resource assignment**: Project planners tend to ignore the specific assignment of resources to activities; instead, concentrating more on start and finish dates. In contrast, process planners—those at the construction site who organise and perform work—must plan for the
allocation of resources. Workers who need to install unique materials with specific tools and equipment should know what task is ahead of them, so they can plan how and where the work will be done and make sure all that is needed will be available when needed (Ballard and Howell 1997).

When allocation planning is done in advance of activity execution, opportunities exist to optimally choose which activities to perform first and when. How much in advance of execution this planning process should take place is controlled by the complexity of the work to be performed and the uncertainties associated with that work and the process it is part of. It has to be remembered, that even the best plans may fail when uncertainties appear during process execution, so good process design must include a contingency plan to recover from these changes.

6. Flow path and sequencing: It may not be clear what the sequencing is of work to be performed (e.g., whether or not an activity will precede another, one), what route is to be taken when handling materials, etc. Such decisions may have to be during construction, when the relevant decision variables take on specific values, or they may have to be decided on stochastically at that time.

Uncertainty is a major culprit for the creation of waste. Waste is created when several resources are needed simultaneously for an activity to start, but a missing one causes the others to become idle. This creates additional work for those keeping track of what is or is not part of them and they occupy space, thus impeding movement and preventing others from using that space. Waste also is created by the lack of detailed planning and communication of progress. This forces workers downstream in a process to stay flexible, which prevents them from detailing their own plans to optimise their own productivity (Ballard and Howell 1997).

However, uncertainty is not the sole culprit for the creation of waste. Waste also is created by doing work to a standard that is well below the optimum. This may be the product of poor work methods design (which means deciding which tools or equipment to use, how to
efficiently sequence processing steps, what personnel training to provide, etc.). Alternatively, it may be a product of poor understanding of how the work fits in with other work in the process. For example, it may be easier to travel to the wash-out area by one path (less wasteful) than another more difficult path with interference with other movement on site.

Construction waste can be classified into the following categories:

- Waste from over production,
- Waste from delays,
- Waste from transportation,
- Waste from unnecessary processes and subprocesses,
- Waste from excess inventory,
- Waste from unnecessary movements, and
- Waste from defects.

Many tools and techniques developed over the past few years have concentrated on a total process level, that being the whole construction process involving Civil, Mechanical and Electrical. The interest in this research project is expressly concentrated at an activity level – concrete delivery and placement.

4.5.1 Variability and waste in concrete operations
Consider the process of concrete delivery and finally placement using a concrete pump. This process can be characterised as two main cycles:

1. Concrete is ordered, batched, loaded into a ready-mix truck, and delivered to the site, and
2. On arrival at the site the concrete will be slump tested to ensure that the concrete meets the required specification, if acceptable then the ready-mix truck positions
itself at the concrete pump (queuing for the next available space if the pump is busy), discharges its concrete into the hopper of the pump, travels to the wash-out area to have all excess concrete washed away and then finally leaves site to make its return to the batching plant.

The variability in this model is characteristic of processes that involve handling bulk materials. However, planning the delivery of ready-mix concrete requires extra care (as compared to gravel, for instance). A batch will start to set approximately 45 minutes after water has been added to the mix (many suppliers will batch a dry mix and only add water when they are closer to the final destination – possibly affecting the quality?). If it has not been placed in its final position by then, it will have to be discarded as stirring up the concrete any time thereafter would destroy the development of its structure and result in a reduced ultimate strength. Thus, one source of uncertainty is the duration needed to bring concrete to the site and place it – if that duration exceeds a threshold value, then the mix is wasted.

Another source of uncertainty is in estimating the quantity required for a particular structure or pour. An order of concrete will reflect not only the amount to be placed in forms (ignoring the volume of reinforcing bars, chairs, spacers, etc.), but also losses of material incurred on a daily basis. Handling quantities are limited in size but they must add up to the required placement quantity as it is important that construction joints be executed as planned rather than be created haphazardly as the result of materials shortage.

Some concrete will be wasted in the handling process because it is a material without packaging of its own. While measuring systems in computer-controlled batch plants are reasonably accurate, there will always be some concrete adhering to the ready-mix truck's revolving drum, the shoot, and the hopper with its placement attachments; concrete will have to be used for slump testing and forming cubes for further testing; some may be spilled when filling buckets or forms, etc. Because concrete is an expensive material and shortages can be very costly, quite a few waste factors are an integral part of the estimate and orders tend to be conservative.
A very important, and often overlooked, variability in construction processes is the skill and experience of the personnel involved. Production can be greatly reduced when a team is put in place that are both unfamiliar with one another and lacking in skill and experience.

4.5.2 Eliminating non value adding activities and simplifying the operation

Thomas et al (1992) suggest that reducing waste and simplifying operations should improve system responsiveness and reduce variability. The presence of waste and excessively complex operations makes things more time consuming and costly than needed. If variability is increased on site, it makes responding to changes and unforeseen circumstances extremely difficult, requiring excessive resources to deal with the changes.
Until now, we have treated concrete delivery and placing as one process, which include two main cycles. However, by applying lean thinking and taking into account the principles that have been discussed it may be possible to simplify this process. This cannot and should not be undertaken without care and consideration. Figure 4.2 shows the concept of eliminating non value added activities and simplifying the operation (Shaded boxes represent non value added activities and Unshaded represent value added activities)
waste and simplifying the operation if lean principles are applied in their purest and strictest sense.

According to lean principles, waste is eliminated by removing unnecessary or non value added steps from the conversion technology. Removing constraints will also improve flow reliability. In Figure 4.2, the process of concrete delivery and placement has been divided into the two main cycles that have been recognised and discussed earlier. The first cycle being at the batching plant and the second at the delivery location of the concrete. Lean construction attempts to simplify a model which is particularly well defined in the first place, and it is important that its success in doing this is examined.

Firstly, at the batching plant the constraint of waiting for the raw materials has been removed. This has been made an integral part of the ordering process and it is assumed that an order will not have been processed unless the required raw materials are available. At the ordering stage, it will also be possible to calculate how many trucks are available and the number of trucks required to meet the customer’s demands. This simplified version of the batching process is shown in Figure 4.2b.

Secondly, the cycle at the concrete’s final destination can be considered. The constraint of waiting for the delivery of the concrete is removed from the process and this, as previously discussed, could be theoretically done via Just In Time (JIT). The testing of the concrete on arrival is made an integral part of the concrete placing and a member of the placing team will be responsible for this, giving them ultimate control of the concrete to be placed. Finally, the subprocess of having the trucks washed before leaving the site will be thoroughly researched depending on the location of the concrete pour and a route clearly set out for the truck driver to follow. This simplified version of the site process is shown in Figure 4.2c. Additional waste will be eliminated if this takes into account other process movements that may be happening simultaneously.

Unfortunately, in theoretically applying Lean principles to the concrete batching and placing process, we see an immediate problem: that of travel to and from site. According to the rules
of lean (Koskela, 1992) travel to site is a flow or non-value adding activity which, if removed, improves the overall effectiveness of the process. But how can travel be removed? Can we really, in practice, eliminate or reduce this ‘non-value adding’ activity? The only way to definitely eliminate it is to have the concrete batched at the site itself, and transported immediately via pump, hopper or conveyor to the placement point. Such an operation is possible, perhaps, on sites where concrete volumes are very large yet overall footprints are small. Examples maybe power stations or dams, yet these projects are few and far between and would not be set up to simply be lean: their physical nature makes them so.

Alternatively the travel time could be reduced by reducing variability of this activity (see section 4.3.3) by locating the batching plant where the roads between it and the project site are clear and free from traffic. This is possibly the most pertinent solution but is not always going to be possible. Batching plants are in fixed positions and the locations of construction sites are not. In other words, for most projects, the location of batching plant is not managed.

In reality, the travel activities which are originally known as flow are in actual fact not removable and should not be shown as shaded. This goes against the principles of lean production and construction but a more realistic version of the ‘Lean’ concrete placing process is shown in Figure 4.3. In this figure, the travel activities are shown as conversions (i.e. unshaded) and we are left with a model which is more satisfactory.

**Figure 4.3:** Eliminating non value added activities and simplifying the operation: travel is now shown as an essential value-adding activity
These improvements, whilst appearing to be straightforward, could reduce waste, but the level of reduction will also be dependent on many other factors:

- A member of the contractor’s project staff has re-calculated the quantities of concrete necessary and has passed this information on to the foreman of the placing team, who will then be responsible for coordinating with the concrete supplier.

- A multi-skilled team is in place with experience and the appropriate skills for carrying out the task. This team should have responsibility for coordinating with preceding teams (formwork team) to best plan the start date for the concrete pour. They will be responsible for having all plant necessary in place for that time and ensure that no other commitments have been made on site that may disrupt the operation.

- Process transparency (as discussed earlier) is very important as it allows changes and alterations to be made during a concrete pour. Good communication between the placing team and concrete supplier is critical throughout the pour. This allows both to make adjustments depending on changes that may occur. This will ultimately result in a reduction of waste, e.g. if a breakdown has occurred in the concrete pump the placing team can inform the supplier who can in turn halt any more trucks being sent out until the problem is rectified.

- As non value adding activities can be caused by both idleness at the concrete pump due to insufficient concrete being available on-site and also from too many trucks queuing waiting to be served by the concrete pump, it is important to match supply with demand. This will ultimately be the responsibility of good communication between the supplier and the customer.
4.6 Introducing the new methodology into the UK construction industry

The methodology introduced in this chapter highlights one main recommendation: the share of non value adding activities in all processes and subprocesses has to be systematically and constantly decreased. Increasing the efficiency of value adding activities has to be continued in parallel.

Introducing the new set of principles in concrete delivery and placement requires thorough planning. Many of the personnel involved in this process will have been working to the same standards for many years, and whilst it may be impossible to change the view of the majority over night, making small gradual steps will reap rewards immediately. The changes are not complicated and do not require vast financial input. Introducing multi-functional teams and making all involved in the process accountable will be a good first step.

Work processes must be made transparent by charting them. Next, the inherent waste in processes must be made visible through suitable measures and targets, and monitoring should be focused on it. As discussed earlier, a significant issue is to find measures which are project independent. Even if measurements are not as straightforward as in manufacturing, they are not an insurmountable problem.

In the following chapters, based on live raw data (discussed in Chapter 3) collected on several construction sites, results highlighting the variability and waste inherent to concrete operations shall be introduced and it will be shown how measurements can be made to increase efficiency in this process.
4.7 Chapter Summary

The production philosophy of Lean Construction has origins that can be traced back to the development and experiments of the JIT production system and quality control in Japan in the 1950s. The basis for this new philosophy has been used in such industries as car manufacturing and electronics; the challenge has been in trying to make it apply to the dynamic field of construction.

In many ways, the concept of applying lean thinking has in the past been concentrated at a total process level, taking into account a multitude of varying activities. The interest in this research project is expressly concentrated at an activity level – concrete delivery and placement. Has it been possible to apply the principles of lean construction at this level?

The answer is possibly, but by no means definitively. The core of lean thinking is in the observation that there are two kinds of experiences in all production systems: conversions and flows. While all activities expend cost and consume time, only conversion activities are seen to add value to the material or piece of information being transformed into a product. Thus, the improvement of flow activities should primarily be focused on reducing or eliminating them, whereas conversion activities should be made more efficient. Traditionally only conversion activities have been considered. This has lead to flow activities, on the whole being overlooked resulting in processes with many uncertainties resulting in an increase in non value adding activities.

A number of principles have been developed for flow design and improvement. The implementation of these principles are key to the improvement of the efficiency of these flow processes:

1. Reduce the share of non value adding activities
2. Increase output value through systematic consideration of customer requirements
3. Reduce variability
4. Reduce the cycle time
5. Simplify by minimising the number of steps, parts and linkages
6. Increase output flexibility
7. Increase process transparency
8. Focus control on complete process
9. Build continuous improvement into the process
10. Balance flow improvement with conversion improvement
11. Benchmark

In this chapter, a discussion of a more radical methodology to the flow activities in concrete delivery and placement by using and understanding the eleven principles listed above. Reducing the share of non value adding activities is at the heart of these; for the process under investigation it was shown that for a start managing the variability within the process and reducing the cycle time went some way to improving the overall process.

Variability and waste within the concrete delivery and placement process was identified and recommendations were made to both improve them and ultimately eliminate them. The whole process was theoretically simplified, eliminating the inherent waste, and two distinct models – one at the concrete batching plant and one at the concrete’s final destination (e.g. construction site) – were developed. Unfortunately this model had the flaw that the travel activities, previously assigned as flows, could not be effectively removed from the process. In reality, however, these activities are intrinsic to the process and should more correctly be considered conversions and this is instinctively so: travel ‘converts’ the location of the value-adding material into a position where it can now be used. A final model is therefore shown, in Figure 4.3, which contains all of the conversion activities but with the elimination of the queuing activities. It is this final model which remains as the conclusion of this chapter and is one which will be revisited in the study of simulation in chapter 6.
Chapter 5

Regression Analysis and Modelling

The concrete supply and delivery process has been described and its stochastic nature has been identified as a problem for which a deterministic solution does not exist. Multiple Linear Regression Analysis will be presented as a potential method for both providing an estimator for this stochastic system and investigating the significance of, and the relationships between, the factors within that system.
Chapter 5 Regression Analysis and Modelling

5.1 Introduction

Multiple Linear Regression Analysis is a significant mathematical tool. Its widespread use within chemical and biological sciences, the social sciences and applied engineering problems suggest that it is a tool which allows investigators to consider their problems in a succinct manner. It can be used for different aims: for example the behavioural scientist may wish to investigate which of many observed factors have the greatest effect on a system, or to confirm a hypothesis that a factor has little influence. It is used in this study as it readily allows a comprehensive model to be developed that reflects the concreting process under investigation. More specifically, to determine the values of parameters for a function that cause the function to best fit a set of observed data. As well as allowing such a model to be developed it can confirms those factors that influence the process and will ultimately rank them in order of importance and significance to the process. This chapter presents fuller and further analyses of work that was conducted earlier in the project and published in 2003 (Dunlop and Smith, 2003) which can also be seen in Appendix 1.

Regression analysis is a powerful statistical technique for applications which seek to analyse industrial processes (Draper and Smith, 1998). At its simplest level of explanation, the essential components of the concrete process are batching, delivery, placement, settlement and curing. The fundamental objective is to place a given volume of concrete and the time taken to place that given volume is influenced by a number of factors such as weather, type of pour and number of truck mixers available. Regression is an appropriate statistical technique for analysing data of this type, producing a linear model that relates to the time required to the most significant variables. It has been successfully used to consider the similar problem of earthmoving (Smith, 1999).

Firstly, the theory behind regression analysis must be looked at and studied in order to provide a good grounding for carrying out analysis and developing a model that may be
used in future operations. Hogg and Ledolter (1992) provide an ideal summary of regression analysis, specifically for physical sciences and engineering, and this has been used extensively in this study.

The goal of this analysis is to develop a model that predicts and calculates the productivity rate for an average concrete pour. This can be done by finding the time required to complete a concrete pour – its duration – as the volume of concrete will already be known. The productivity rate will therefore be the total volume divided by the duration. The difficulty in this type of exercise is in the selection of the explanatory variables to be analysed in order to predict the total pour duration. Some of the more obvious variables, such as the total volume of concrete required, and perhaps some of the not so obvious ones, such as weather and time of year, are discussed in detail in this chapter.

The data used in this study are from the Tay Wastewater Treatment Project, Aberdeen Wastewater Treatment Project, M6 Thelwall Viaduct and the Inverness Wastewater Treatment Project. The data from the Falkirk Millennium Canal Project has not been used as input data, but will be used in order to validate the final model.

There are various techniques that can be used in regression analysis (Hogg & Ledolter, 1992); this study will use backward stepwise regression analysis. A full set of explanatory variables is used in the first instance and the insignificant variables are removed after each run until all those remaining are deemed statistically significant. Once this final model has been developed it must then be subjected to various statistical tests, such as residual checks and sensitivity analysis, to ensure that the assumptions behind regression modelling have not been violated and that it provides a true representation of the input data.

5.1.1 Non Linear Regression

This chapter will set out to develop linear models of the concrete placing process, as introduced above. A linear model is one which data is transformed into a linear format. Sometimes, however, the data cannot be transformed in this manner and a non-linear model
must be fitted. Mathematically, however, the two methods are very different and models provided by non-linear analysis can sometimes be more inflexible in use. Certainly, if there is an option, 'it is generally best to perform [a linear] transformation when possible' (Hayter, 1996, p. 731).

In section 5.10.2, the adequacy of the fitted linear models is investigated, which considers the coefficients of determination ($R^2$); the significance of the explanatory variables; the fit of the output; and the variability of the residuals. The conclusions were that the linear model provided a satisfactorily adequate fit and thus is was deemed unnecessary to investigate non-linear models further.

5.2 Regression Analysis Explained

Regression analysis is used to study the relationship between measurable variables. It is a widely used tool as it can provide a comprehensive method for establishing a functional relationship between variables. In regression analysis, independent variables are used to model a response variable. In the rare instances the relationships are known exactly so that the response and explanatory variables are functionally related, such relationships are called deterministic. In many cases, such as our concrete supply and delivery process, the relationships are not known and, furthermore, are much too complicated to be described by a small set of explanatory variables. In such instances it is necessary to approximate the relationships and develop models that characterise their main features, these models are statistical in nature. Regression models can be used for:

- Providing a good description of the behaviour of the response variable
- Variable screening
  - Parameter estimation
  - Prediction of future responses
- Control of a process by varying levels of input
- Developing realistic models of the process
There are two main types of regression model: simple linear regression model, in which the relationship between a response and a single explanatory variable is approximated by a linear function, and the more complex multiple linear regression dealing with more than one explanatory variable.

5.3 Simple Linear Regression Model

Considering one explanatory variable, \( x \), and assuming that the statistical relationship between the response variable \( Y \) and this explanatory variable is linear, it is possible to write the model as:

\[
Y_i = \beta_0 + \beta_1 x_i + e_i \quad i = 1, 2, \ldots, n \quad \text{Equation. 5.1}
\]

The usual assumptions about the parameters and variables in this model are the following:

1. \( x_i \) is the \( i \)th observation on the explanatory variable. In planned experiments the known constants \( x_1, x_2, \ldots, x_n \) correspond to particular settings of the explanatory variable that are chosen by the investigator.

2. \( Y_i \) is the response that corresponds to the setting \( x_i \) of the explanatory variable, \( i = 1, 2, \ldots, n \)

3. \( \beta_0 \) and \( \beta_1 \) are the coefficients in the linear relationship; \( \beta_0 \) is the intercept and \( \beta_1 \) is the slope. A change of one unit in the explanatory variable \( x \) translates into a change of \( \beta_1 \) units in the response variable.

4. The random variables \( e_1, e_2, \ldots, e_n \) are errors that create the scatter around the linear relationship \( \beta_0 + \beta_1 x_i, i = 1, 2, \ldots, n \), respectively. We assume that these errors are mutually independent and normally distributed with mean zero and variance \( s^2 \). That is,

\[
E(e_i) = 0 \quad \text{and} \quad \text{var}(e_i) = s^2, \quad i = 1, 2, \ldots, n;
\]
furthermore, the information from one error does not imply something about another.

5.3.1 Estimation of Parameters

There are three parameters in the simple linear regression model: the coefficients $\beta_0$ and $\beta_1$ in the regression function and the variance $s^2$, which accounts for the random scatter around the regression line. Ordinarily, these parameters are unknown and must be estimated from sample data.

The method of least squares is used by virtue of its simplicity and is used more extensively than any other estimation procedure to estimate the unknown parameters. The least square estimation uses the criterion that the solution must give the smallest possible sum of squared deviations of the observed $Y_i$ from the estimates of their true means provided by the solution. The sum of squares measures how close the regression line is to the observations. If the regression line goes through all observed points, the sum of squares will be zero.

So in order to get an estimate of $\beta_0$ and $\beta_1$ it is necessary to set the two first partial derivatives equal to zero. This gives us:

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x}$$  \hspace{1cm} Equation. 5.2

and

$$\beta_{1e} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sum (x_i - \bar{x})^2}$$  \hspace{1cm} Equation. 5.3

The data observed can be used to find $\hat{\beta}_0$ and $\hat{\beta}_1$, the estimates of $\beta_0$ and $\beta_1$, the equation

$$\hat{Y}_i = \hat{\beta}_0 + \hat{\beta}_1 x_i$$  \hspace{1cm} Equation. 5.4

is then used to calculate the predicted value for $Y_i$. 


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The variance \( \sigma^2 \) is of great importance, as it is a measure of the adequacy of the fitted line in predicting \( Y \) and can be found from:

\[
\sigma^2 = \frac{\sum (y_i - \hat{y}_i)^2}{n-2}
\]

Equation. 5.5

5.3.2 Residuals

Residuals can be defined as the difference between an observation \( y_i \) and the predicted value \( \hat{y}_i \), and can be calculated using:

\[
e_i = y_i - \hat{y}_i
\]

Equation. 5.6

The usual assumptions made when performing a regression analysis are that the errors have a mean of zero, have a common variance \( \sigma^2 \), and follow a normal distribution.

5.4 Multiple Linear Regression Model

As previously stated, multiple linear regression models deal with more than one explanatory variable and take the form:

\[
Y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_p x_{ip} + \varepsilon_i \quad \text{where } i = 1, 2, \ldots, n
\]

Equation. 5.7

and has similar assumptions to the simple linear regression model (Smith, 1999) i.e.:

1. \( Y_i \) is the response that corresponds to the levels of the explanatory variables \( x_1, x_2, \ldots, x_p \) at the \( i \)th observation.
2. \( \beta_0, \beta_1, \beta_2, \ldots, \beta_p \) are the coefficients in the linear relationship. For a single factor \((p = 1)\), \( \beta_0 \) is the intercept, and \( \beta_1 \) is the slope of the straight line defined.

3. \( e_1, e_2, \ldots, e_n \) are errors that create scatter around the linear relationship at each of the \( i = 1 \) to \( n \) observations. The regression model assumes that these errors are mutually independent, normally distributed, and with a zero mean and variance \( \sigma^2 \). It is important that this constant variance assumption holds, but in reality this is sometimes difficult to achieve.

5.4.1 Estimation of the Regression Coefficients

Due to the complexity of estimating the unknown regression coefficients \( \beta_0, \beta_1, \ldots, \beta_p \), a dedicated computer programme can be used, for example, SAS, SPSS and MINITAB. In this instance the Data Analysis add-in for Microsoft Excel has been used to perform the required regression analysis.

An analysis of variance (ANOVA) table provides an overall summary of the results of any multiple regression analysis. An example of an ANOVA table can be seen in Table 5.1.

Table 5.1: An Example of an Analysis of Variance (ANOVA) Table

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares (SS)</th>
<th>Degree of Freedom (df)</th>
<th>Mean Square (MS)</th>
<th>F Value (SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>SSR</td>
<td>( p )</td>
<td>MSR = SSR/( p )</td>
<td>MSR/MSE</td>
</tr>
<tr>
<td>Residual</td>
<td>SSE</td>
<td>( n - p - 1 )</td>
<td>MSE = SSE/(( n - p - 1 ))</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>SSTO</td>
<td>( n - 1 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Within the ANOVA table a number of definitions need further explanation and this shall be done below (reference should be made to Table 5.1):

- Column 1 shows the source of variation
- Column 2 gives the corresponding sums of squares (see page 128). The total sums of squares is partitioned into a sum of squares due to regression (SSR), a sum
of squares due to error (SSE) and finally the total sum of squares (SSTO). These can be calculated as shown below:

\[ SSR = \sum_{i=1}^{n} (\hat{Y}_i - \bar{Y})^2, \quad \text{Equation. 5.8} \]

\[ SSE = \sum_{i=1}^{n} e_i^2, \quad \text{and} \quad \text{Equation. 5.9} \]

\[ SSTO = SSR + SSE \quad \text{Equation. 5.10} \]

- Column 3 contains the degrees of freedom for the various sums of squares. The degrees of freedom can be thought of as the number of independent components that are necessary to calculate a sum of squares. Where,

  - \( p \) = number of explanatory variables, and
  - \( n \) = the number of data points.

- Column 4 in the ANOVA table is called the mean-square column; it contains the ratios of the various sums of squares and their degrees of freedom. MSR is the mean square due to regression, and MSE is the mean square due to error, and is an unbiased estimate of \( \sigma^2 \).

- Column 5 shows the F-ratio, \( F = \frac{MSR}{MSE} \), which is a statistic for testing whether or not \( \beta_1 = 0 \). The F-ratio may be used to test for the significance of the overall dependence of \( Y \) on the variables \( x_1, x_2, \ldots, x_p \).

  - If \( F > F (\alpha; 1, n - 2), \beta_1 \neq 0; \) this means that \( x \) provides significant information for predicting \( Y \). Where \( \alpha \) is the confidence level.

  - If \( F < F (\alpha; 1, n - 2), \beta_1 = 0; \) this means that \( x \) provides little or no help in predicting \( Y \).

As well as the F-ratio, there is another check to calculate how well the regression equation fits the data in form of the coefficient of determination, \( R^2 \). It is given by

\[ R^2 = \frac{SSR}{SSTO} = 1 - \frac{SSE}{SSTO}, \quad \text{Equation. 5.11} \]
'Sum of Squares' are measures of the amount of variability within a dataset. Ideally we wish our regression model to explain all of the variability within this dataset but realistically it will not – some of the variability will remain unexplained. This could be for one of two main reasons: either the original dataset contains errors that are due to flaws in the original data collection or observation process; or, the data contains relationships between its variables that the model is unable to explain – perhaps, in our case, because the relationships are non-linear. As the ideal situation is for all of the variability to be explained by the model then the sum of squares due to the regression model (SSR) should be high relative to the sum of squares due to the errors (SSE). Therefore, as \( R^2 \) approaches 1 we reach our ideal regression model in terms of its ability to express the full stochastic nature of the data. In other words, since since \( SSR = SSTO - SSE \) it follows that

\[
0 \leq R^2 \leq 1.
\]

A high \( R^2 \) value indicates that the regression model with the \( p \) explanatory variables explains a large proportion of the variability among the observations \( y_1, y_2, \ldots, y_n \). However, this value by itself does not tell us which of the \( p \) variables are the most important.

It is also possible to show that the F-ratio and \( R^2 \) are related through the very simple equation

\[
F = \frac{R^2}{1-R^2} \left( \frac{n-p-1}{p} \right). 
\]

Equation. 5.12

A high \( R^2 \) implies a large value for the F-ratio.

A closely related measure of fit of an estimated regression model compares the variance estimates with and without the explanatory variables. That is, the sample variance estimates
of the observations \( y_1, y_2, \ldots, y_n \), which is \( \frac{SSTO}{n - 1} \), can be compared to the variance estimate in the regression model, \( MSE = \frac{SSE}{n - p - 1} \). The proportionate reduction in variance due to regression is the adjusted \( R^2 \), namely,

\[
R_a^2 = 1 - \frac{SSE}{n - p - 1} \left( \frac{1}{SSTO} \right) \left( n - 1 \right).
\]

Equation 5.13

It can be shown that \( R_a^2 \leq R^2 \).

5.5 Regression Model to be used in Study

To recapitulate, the main purpose of the study in this chapter is to carry out a regression analysis on the observed data to obtain a model that will estimate productivity rates of concrete operations. Such a model will help planners and estimators to make allowances and hence better the overall performance of concrete operations.

The regression analysis method used will be multiple linear regression and in particular backward elimination, stepwise regression. This involves starting with a full set of explanatory variables in the model and eliminating ‘non-significant’ variables one at a time until all the remaining variables are ‘significant’. At any step the variable with the smallest absolute t-statistic, that is the ratio of the co-efficient to its standard error, will be eliminated; a large t-ratio is therefore desirable. The manner in which it is decided whether a t-ratio is large enough to be significant is by comparing it to a critical t-ratio. The critical t-ratio is calculated using information about the input data, namely the number of observations and the number of explanatory variables. The formula used to calculate the critical t-ratio is as follows:
\[ t_{\text{critical}} = t(\alpha/2; n - p - 1) \]  

Equation. 5.14

Where \( \alpha \) is a measure of the confidence limit (CL) of the model and defined by:

\[ CL = 100(1 - \alpha) \]  

Equation. 5.15

The \( t \)-ratio is then calculated using the upper percentage points of the Student’s \( t \)-Distribution, as shown in Table 5.2.

For example, at a significance of 5%, with 202 observations and 9 explanatory variables, \( t \) (0.025; \( n - p - 1 \)) = 1.98. This implies that all variables with an absolute \( t \)-ratio < 1.98 are not significant to the regression model.
Table 5.2 Upper Percentage Points of the Student's t-Distribution: Values of $t (a ; r)$,

<table>
<thead>
<tr>
<th>r</th>
<th>$a = 0.10$</th>
<th>$a = 0.05$</th>
<th>$a = 0.025$</th>
<th>A = 0.01</th>
<th>$a = 0.005$</th>
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<td>3.077684</td>
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Once the critical t-ratio is determined, the least significant variable is removed from the model, i.e. the one with the lowest absolute t-ratio. After this variable is removed the regression is carried out again with the reduced number of variables, changing all necessary statistics. Variables are removed one by one until all remaining variables are statistically significant.

Now that the theory behind the regression analysis has been introduced it is now necessary to look at the data to be used in the study and then identify the explanatory variables to be analysed.

5.6 Data used in Regression Analysis

The data collected from the projects introduced in Chapter 3 are used in the regression analysis. These were taken from the Tay Wastewater Treatment Project, Aberdeen Wastewater Treatment Project, M6 Thelwall Viaduct and the Inverness Wastewater Treatment Project and formed the main input data for the analysis. The data from the Falkirk Millennium Canal Project has not been used as input data, but will be used in order to validate the final model. This is a vital part of any model development as the consequences of using a model which does not reflect the true nature of the operation could be very counter-productive.

In total the four projects forming the main input to the model represent 316 concrete pours and the model will be validated using 29 concrete pours.
5.7 Choosing the Explanatory Variables

As we are trying to model the time taken to complete concrete pours it is important to chose the explanatory variables within the concrete placing system very carefully. These should be easily measurable – an unmeasurable, or non-estimatable input being of no use in a prediction model – and show completeness and simplicity. For the concrete operations that have been observed for this study it was apparent that there are an abundance of factors that affect the time taken to complete a concrete pour. Some of these may be quite obvious, nevertheless, many of the variables used in this study are a direct result of the investigator having the opportunity to observe many of the concrete pours at first hand.

It is particularly difficult to capture every variable present in such a system and it has been the experience of the investigator that someone, with hindsight, will always propose a variable that may not have been directly included in the study. Some of these will have been ignored, or better still not considered, due to their complexity and problematical nature. As indicated above, all of the variables considered also share one other advantage and that is the ease of which they can be predicted and planned. This makes it possible for a contractor to estimate the total time required for a concrete pour well in advance of it actually taking place.

The explanatory variables considered in regression models can usually take values over some continuous range. Occasionally it is necessary to introduce a factor that has two or more distinct levels. For example, data may arise from two sites, or three concrete pumps, or five batching plants. In such a case a continuous scale cannot be set up for the variable “site” or “pump” or “batching plant”. It is necessary to assign these variables some sort of level in order to take into account that they have separate deterministic effects on the response variable. The explanatory variable for ‘Time of Year’ is an indicator of seasonality and is common to regression models (Chaterjee and Price, 1991, p. 116). These qualitative variables are called indicator or dummy variables and are usually, but not always, unrelated to any physical levels that might exist in the factors themselves.
The use of such ordinals in regression modelling must be done with care as their interpretation is different from integers in which their value is a direct indicator of the nature of the variable. In particular, using indicator variables for the type of pour, or project studied for example, is prone to problems if the same 'coding' system is not used with the model in practice. Charterjee and Price, 1991; and Kmenta, 1997 provide good discussions on the use of ordinals and qualitative variables in regression.

A total of eight variables were measured and recorded from each of the projects and a short description and the reason why they were chosen will follow.

5.7.1 Total Volume of Concrete Delivered

It is no surprise that this is the first variable to be introduced. Before any analysis has been carried out it can instinctively said to one of the most fundamental factors in any concrete pour. This will be the total volume, in cubic metres, of concrete delivered by the supplier. Whilst this will not always be the volume ordered by the contractor at the beginning of pour, due to last minute changes etc., it will almost certainly be closely linked. Intuitively, it may be assumed that concrete volume is directly proportional to the pour's duration. We have to be careful with such an assumption as we also know that rate of pour has to be controlled for some shapes of structures, and this leads us to the proposal of the next explanatory variable:

5.7.2 Type of Concrete Pour

Due to the fact that every construction project is unique – one off – there are many different concrete pours encountered from project to project, and indeed within the same project. A good example of why concrete pours are often difficult to plan and execute. From observing the concrete pours it was decided that pours could be split into three main categories: Wall, Column and Base pours.

Wall pours are usually small in volume and require very well timed concrete delivery and slow controlled placement. This means that these pours can produce relatively low productivity levels. Like Wall pours, Column pours have to be carried out in a slow
controlled manner to avoid structural deformities and sagging occurring. Both of these types of structures can take many forms and are very different from Base pours. Base pours are ideally carried out in a fast, steady manner and this requires very good communication between the contractor and the supplier in order to maintain a continuous supply of concrete. Base pours are usually found in the upper range of productivities.

The type of pour is an indicator variable and in this case, has been assigned a numerical code with Wall pours being 1, Column pours being 2 and Base pours being 3.

5.7.3 Average Volume of Delivery Trucks

It could be more useful to think of this as the average capacity of the delivery truck; however, it is also quite common for delivery trucks to be below capacity, so we will deal with the average volume delivered per load. The majority of concrete delivery trucks in the UK have a capacity of either 6 or 8 cubic metres.

During concrete pours it is advantageous to have as much concrete delivered as possible in each load, so therefore 8 cubic metres. This will ultimately reduce the number of loads required therefore reducing cost and the time required to complete the pour. This will also, clearly, affect the number of trucks available on each pour.

5.7.4 Number of Trucks Available on Each Pour

The number of delivery trucks available on each pour can greatly affect the overall pour duration. If too few trucks are assigned to a particular pour then there will be prolonged periods where the placing team and concrete pump will be idle, hence lengthening the pour duration. It is also not to the contractor’s advantage to have an over-allocation of delivery trucks on pours, as this will result on long queues on site, possibly having a detrimental affect on the placing team. What should be remembered is that there will be an optimum number of trucks on each and every pour. By including this factor in the regression analysis it hoped to highlight this point.
The number of trucks on each pour is entered directly as an integer.

5.7.5 Weather

The UK climate is, of course, infamous for its unpredictability and often has an affect on the performance in the UK construction industry. Concrete operations, like many other outdoor construction processes, are weather dependent and will usually only take place during times of settled weather. Extreme weather conditions may have an affect on the performance of the placing team and the regression analysis should indicate the significance of this factor.

Another reason for including weather as a factor in the regression model is that it also is possible to estimate ground conditions from the weather. Clearly, during periods of persistent rain vehicles may find it difficult to manoeuvre on site, thus, lengthening the duration of the concrete pour.

Weather has been divided into 3 categories and each has been assigned a numerical value, they are: Overcast = 1, Sunny = 2 and Rain = 3.

5.7.6 Start Time

The start time of the concrete pours has been included as a factor, from the investigators observations on site. In observations of the concreting operations there appeared to be an occasional lack of motivation amongst the placing team and the plant operators, which was affected by the start times. An early morning start, or indeed a late start, would often result in the workers performing well below their optimum level. Unfortunately the affect on output was not directly measurable and this variable has been included to investigate its significance.

The start time was divided into 3 different sectors and each was assigned a numerical value from 1-3. Start time before 9am = 1, 9-3pm = 3, after 3pm = 3.
5.7.7 Time of Year

The main influence the time of year has on the construction industry is the amount of daylight hours during certain seasons. It is for this reason that time of year has been included as an explanatory variable.

Again, this is regarded as a dummy variable and has been separated into the four seasons of the year.

5.7.8 Project

This particular variable has been included to test whether or not there are significant differences between the way the projects are operated and managed. This is a very useful factor to include in this study, as each contractor will undoubtedly have different approaches to concrete operations.

If this variable is found to be significant to the dependent variable and remains in the model it has to be realised that it cannot be used in a predictive model. The main purpose of having it in the model is only to compare the different projects under investigation. It is a dummy variable and each project has been assigned a numeral between 1 and 4.

These eight explanatory variables form the basis for the regression analysis and the data for the 368 concrete pours have been stored in an Excel spreadsheet.

Before a regression analysis can be carried out on the collated data it is important to carry out several statistical tests to ensure that the data is suitable for a regression analysis. These procedures will be introduced in the next section of this chapter.
5.8 Data Preparation

To summarise, the objective of the analysis is:

1. To investigate the significance of the exploratory variable, project. By doing this, we will hopefully have a better understanding of the effect different approaches on different project have on overall concrete pour duration.

2. To build a reliable relationship that will represent the interaction between the measured explanatory variables, under existing conditions, using the data recorded on the four projects.

3. To validate the resulting relationship by using data from a fifth project, which is independent to the others.

The aim is that the model can then be used to estimate the total duration of concrete pours on future pours.

The analysis requires a careful study of the nature of the observed variables, together with the existence of any natural interactions between them. It may also be necessary for the data to be mathematically transformed into a more meaningful form.

5.8.1 Transformation of Data

A convenient starting point in the preparation of data for regression analysis is that the model describing the data is linear in the variables. In order to achieve this it is often necessary to carry out the analysis on transformed variables. The necessity for transforming the data arises because the original variable violates one or more of the standard assumptions. The most commonly violated assumptions are those concerning the linearity of the model and the constancy of the error. A regression model is linear when the parameters present in the model occur linearly.

If we look at an example from the data more closely a few points will arise that require attention. It is possible to assume that there will be a certain amount of proportionality
between the response, total duration of pour, and the total volume of concrete in the pour. This is shown in Figure 5.1, which indicates some linearity between the two parameters. It can be seen that the total pour duration increases as the total volume increases which for the meantime can be assumed to be correct.

What Figure 5.1 also shows is the evidence of an outlier, or extreme data point. An outlier is an observation with a large residual. This type of data point will have a residual that is large relative to the residuals for the remainder of the observations and also have an affect on the slope of the regression line. Outliers may occur because of errors in the gathering or interpretation of the data; or they may be genuine observations that form part of the process under investigation. As Chatterjee and Price (1991, p. 23) put it ‘whichever the case, extreme data points should always be followed up and examined in detail.’ There are statistical methods available to detect and remove outliers but it was decided to investigate this point first to see if such methods were actually necessary.

The point in Figure 5.1 is remarkable because it is for such a large volume. The data was investigated and it was found to be a pour from the M6 Thelwall Viaduct project on 13 July 1993. As suspected, there were problems with this datapoint and these were twofold: firstly, the operation involved not one but three separate concrete pumps. Secondly, the volume of the operation was actually 765m$^3$ and not the 470m$^3$ that had been recorded.

As this datapoint is not representative of the process under study (i.e. one pump systems), is suspect in its recording and is remarkable in its attributes (few concrete pours are as big as 470m$^3$ let alone 765m$^3$) from this point forward this data point has been confidently removed from the data set.
The model under consideration can now be written as:

\[
TIME = \beta_0 + \beta_1 TOTVOL + \beta_2 TYPE + \beta_3 START + \beta_4 TRUCK + \beta_5 YEAR + \beta_6 AWOL + \beta_7 WEATHER + \beta_8 PROJ + e
\]  

Equation. 5.16

Where:

\[
\begin{align*}
TIME &= \text{Total duration of concrete pour} \\
TOTVOL &= \text{Total volume of concrete in pour} \\
TYPE &= \text{Type of pour} \\
START &= \text{Start time of pour} \\
TRUCK &= \text{Number of trucks used during pour}
\end{align*}
\]
This model does pose a few questions that require further explanation. The reader may query why the explanatory variables (with the exception of TOTVOL) have been included in the model in their original metric and a transformation not considered. Individual scatter plots of TIME against the remainder of the explanatory variables show more or less linear relationships. Furthermore, the range of these variables is rather small. Since over a limited range most non-linear functions can be approximated by linear ones, it is of lesser importance whether we use a transformation on the remaining explanatory variables.

The scatter plots of the remaining 7 explanatory variables versus TIME can be seen in Figure 5.2 (a-g).
The next test that will be carried out will check for any existence of natural interactions between the explanatory variables.

5.8.2 Multicollinearity within the Explanatory Variables

In this section further checks will be made to ensure that the explanatory variables are ready to be subjected to regression analysis. An assumption is made in multiple regression analysis that there is no evidence of interaction or correlation between the chosen explanatory variables; this problem is often referred to as multicollinearity.

To discuss multicollinearity among the explanatory variables, let us consider a multiple regression model with 2 regressors, $x_1$ and $x_2$. If $x_1$ and $x_2$ convey the same, or very similar information, we say that there is multicollinearity. If they express the same information through an approximate linear relationship between $x_1$ and $x_2$, then the absolute value of the correlation coefficient, $r_{12}$, is close to 1. On the other hand, if $x_1$ and $x_2$ provide different and independent information, $r_{12}$ is close to zero. If the correlation coefficient between $x_1$ and $x_2$ is zero, we can also say that the $x_1$ and $x_2$ are orthogonal.
As an example of multicollinearity that was encountered at the early stages of this study, consider the total volume of concrete and the total number of loads, $x_1$ and $x_2$ being used in the same study with the dependent variable $Y$ being total duration. Clearly $x_1$ and $x_2$ express similar information because they are directly and linearly proportional; thus $r_{12}$ approaches 1. In real life situations and many practical applications, $r_{12}$ will not be 1 exactly, but it may be very large and this issue must be addressed before one can move on with the analysis.

The first step that must be made, before any mitigation is considered, is to study the correlation matrix, which will give a correlation coefficient for every combination of variables. This can be seen in Table 5.3.

<table>
<thead>
<tr>
<th></th>
<th>Total Volume</th>
<th>Time of Year</th>
<th>Type of Pour</th>
<th>Average Volume</th>
<th>Start Time</th>
<th>Weather</th>
<th>Project</th>
<th>No. of Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Volume</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time of Year</td>
<td>0.1212</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of Pour</td>
<td>0.6054</td>
<td>0.0464</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Volume</td>
<td>-0.119</td>
<td>0.0994</td>
<td>-0.1194</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start Time</td>
<td>-0.2545</td>
<td>0.0766</td>
<td>-0.2863</td>
<td>-0.0992</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weather</td>
<td>0.1319</td>
<td>0.0311</td>
<td>0.0262</td>
<td>-0.039</td>
<td>0.0103</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project</td>
<td>-0.4644</td>
<td>0.0909</td>
<td>-0.3609</td>
<td>0.7066</td>
<td>-0.1042</td>
<td>-0.0704</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>No. of Trucks</td>
<td>0.7999</td>
<td>0.0521</td>
<td>0.5129</td>
<td>-0.3216</td>
<td>-0.1452</td>
<td>0.078</td>
<td>-0.5805</td>
<td>1</td>
</tr>
</tbody>
</table>
As can be seen from Table 5.3 there appear to be several interactions that merit further attention. The most serious interaction is between total volume of concrete and number of trucks used on the pour, with a correlation coefficient of nearly 0.8. This is, perhaps, not totally unexpected; however, it is the view of the investigator that the two variables are explaining and measuring very different things, and to eliminate one of them at this early stage would be difficult to justify. For instance, the number of trucks used on the pour is, as well as indicating the volume of concrete used, suggesting the resource level for the operation which may or may not be ideal.

On any concrete pour there will be an optimum number of trucks servicing the concrete pump, that is to say that there will be no queuing or idleness at any stage of the operation. This is rarely, if ever, the case and it introduces a dilemma that must be given some consideration. First of all, on large concrete pours the contractor may wish for an unlimited number of delivery trucks, but the supplier may not be in a position to offer this due to other commitments and/or lack of resources. Likewise, on smaller pours a contractor may well know that a certain number of trucks will best deliver the concrete, however he may be happy to use less delivery trucks to decrease costs etc.

What often happens on construction projects is that the supplier will dedicate a certain number of trucks to a contractor over the length of the project. The contractor will therefore have these trucks at his disposal regardless of the size of the pour. Consequently, is it really possible to say that the volume of concrete is proportional to the number of trucks used?

This last point may also address the high correlation factor between the number of trucks used and project. Certain projects had a near limitless supply of delivery trucks and others used the absolute minimum number. This would lead to some correlation between the two factors and with a correlation factor of -0.58, it is felt that this issue does not warrant further concern.

The correlation factors of 0.60 between the total volume and the type of pour, and 0.51 between the number of trucks used and the type of pour, also may be related. In concrete
operations it is usual that wall and column pours will be significantly smaller in volume than base pours. This would imply that, yes ideally more trucks will be used on base pours and that yes, the total volume will be greater.

The high correlation factor of 0.71 between the project and the average volume of concrete per truck can also be explained. In the UK, concrete delivery trucks usually have a capacity of either 6 or 8 cubic metres; therefore, the trucks that supplied the projects in the study usually a capacity of one 6 or 8 cubic metres.

While simple correlations tell something about multicollinearity, they must only be used as an initial test. High correlations between two variables that may be easily explained do not necessarily result in multicollinearity. Inspection of the correlation matrix will only reveal bivariate multicollinearity, for bivariate correlations greater than 0.90. In fact, multicollinearity can be very difficult to detect.

The preferred method of assessing whether or not multicollinearity is present amongst the explanatory variables is to regress each independent on all other independent variables in the equation. To assess multivariate multicollinearity, one should use tolerance (TOL) or variance inflation factors (VIF), which build in the regressing of each independent on all the others. It should be noted that even when multicollinearity is present, the estimates for other variables in the regression equation (variables that are not collinear with others) are not affected.

- **Tolerance (TOL) can defined as**

\[
TOL = 1 - R^2
\]

Equation. 5.17

for the regression of that independent variable on all the other independents, ignoring the dependent. There will be as many tolerance coefficients as there are dependents.
The higher the intercorrelation of the independents, the more the tolerance will approach zero. As a rule of thumb, if tolerance is less than 0.20, a problem with multicollinearity is indicated.

When tolerance is close to zero there is high multicollinearity of that variable with other independents and the regression coefficients will be unstable. The more the multicollinearity, the lower the tolerance and the more the standard error of the regression coefficients.

- Variance Inflation Factor (VIF) is simply the reciprocal of tolerance and is given by

\[ VIF = TOL^{-1}. \]

Equation 5.18

Clearly, a value of VIF close to one indicates no relationship, while larger values indicate presence of multicollinearity.

Table 5.4 shows the tolerance and the variance inflation factor for the eight explanatory variables considered in the study. It is interesting to note that the standard error of the regression coefficient is doubled when VIF is 4.0 and the TOL is 0.25, corresponding to a value for $R^2$ of 0.87. This level of VIF (=4.0) is an arbitrary but common cut-off criterion for deciding when a given independent variable displays "too much" multicollinearity: values above 4 therefore are seen to suggest a multicollinearity problem. The literature surrounding this cut-off point is somewhat vague. Some researchers use the more lenient cut-off of 5.0: if VIF = 5, then multicollinearity is a problem. Chatterjee and Price (1977) suggest that a VIF in excess of 10 is an indication that multicollinearity may be causing problems in estimation.
This introduces a certain amount of ambiguity in deciding what VIF to use as the cut-off. In this case, as none of the VIFs in Table 5.4 exceed the lowest cut-off point of VIF equal to 4, it is concluded that at this stage there is sufficiently low level of multicollinearity amongst the variables to not be overly concerned.

### Table 5.4  Tolerance and the Variance Inflation Factor for the eight explanatory variables

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Explanatory Variables</th>
<th>$R^2$</th>
<th>TOL</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTVOL</td>
<td>YEAR, TYPE, AVVOL, START, WEATHER, PROJ, TRUCK</td>
<td>0.7410</td>
<td>0.2590</td>
<td>3.8608</td>
</tr>
<tr>
<td></td>
<td>YEAR</td>
<td>0.0678</td>
<td>0.9322</td>
<td>1.0727</td>
</tr>
<tr>
<td></td>
<td>TYPE</td>
<td>0.4154</td>
<td>0.5846</td>
<td>1.7106</td>
</tr>
<tr>
<td></td>
<td>AVVOL</td>
<td>0.5757</td>
<td>0.4243</td>
<td>2.3566</td>
</tr>
<tr>
<td></td>
<td>START</td>
<td>0.2341</td>
<td>0.7659</td>
<td>1.3057</td>
</tr>
<tr>
<td></td>
<td>WEATHER</td>
<td>0.0328</td>
<td>0.9672</td>
<td>1.0340</td>
</tr>
<tr>
<td></td>
<td>PROJ</td>
<td>0.6931</td>
<td>0.3069</td>
<td>3.2579</td>
</tr>
<tr>
<td></td>
<td>TRUCK</td>
<td>0.6976</td>
<td>0.3024</td>
<td>3.3064</td>
</tr>
</tbody>
</table>

Having firstly prepared the data into an easy to understand state and having carried all necessary tests to show that there is not sufficient multicollinearity amongst the variables to cause particular concern, the next step is to carry out the regression analysis.
5.9 Backward Stepwise Regression Analysis

Having determined the explanatory variables to be considered and having conducted various tests to assess the validity of the data the regression analysis can commence. The first regression analysis is being carried out with PROJECT included as an explanatory variable in order to ascertain its significance in this model. A second regression analysis will then be carried out without including PROJECT as an explanatory variable to provide model that can be used as a predictive tool.

All results will be tabulated in the form of an output summary table showing the regression coefficients, standard errors, t-statistics, P-values and the upper and lower 95% confidence levels and an analysis of variance (ANOVA) table.

All the regression runs carried out will be analysed using a confidence level of 97.5%, making the critical t-statistic, \( t (0.025; n - p - 1) = 1.98 \) (see Table 5.2), since \( n - p - 1 \) will always be greater than 120.

The regression runs in this study will all have a common dependent variable – Pour Duration, known as TIME.
5.9.1 Regression Run 1

In the first regression run, the explanatory variables included are shown in Table 5.5.

Table 5.5 Explanatory variables considered in Regression Run 1

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Explanatory Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME</td>
<td>TOTVOL, YEAR, TYPE, AVVOL, START, WEATHER, PROJ, TRUCK</td>
</tr>
</tbody>
</table>

Table 5.6 shows the estimated partial regression coefficients and the corresponding t-statistics from the regression on TIME for all eight explanatory variables. As can be seen the t-statistics are all relatively large and this is reflected by the $R^2_{adj}$ value for the first run of 0.7761 and the F-ratio of 153.12 shown in the ANOVA table in Table 5.7.
Table 5.6  Estimated partial regression coefficients and the corresponding t-statistics from the regression on TIME for all eight explanatory variables – Run 1

<table>
<thead>
<tr>
<th></th>
<th>Coefficients</th>
<th>t-Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>204.67</td>
<td>5.38</td>
</tr>
<tr>
<td>TOTVOL</td>
<td>1.49</td>
<td>17.59</td>
</tr>
<tr>
<td>YEAR</td>
<td>-8.44</td>
<td>-1.79</td>
</tr>
<tr>
<td>TYPE</td>
<td>-32.02</td>
<td>-6.92</td>
</tr>
<tr>
<td>AVVOL</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>START</td>
<td>-28.90</td>
<td>-4.93</td>
</tr>
<tr>
<td>WEATHER</td>
<td>-4.32</td>
<td>-0.91</td>
</tr>
<tr>
<td>TRUCK</td>
<td>11.58</td>
<td>3.65</td>
</tr>
<tr>
<td>PROJ</td>
<td>16.64</td>
<td>3.33</td>
</tr>
</tbody>
</table>

Table 5.7  ANOVA statistics for regression on TIME – Run 1

<table>
<thead>
<tr>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>8</td>
<td>4672314.35</td>
<td>584039.29</td>
</tr>
<tr>
<td>Residual</td>
<td>343</td>
<td>1308273.95</td>
<td>3814.21</td>
</tr>
<tr>
<td>Total</td>
<td>351</td>
<td>5980588.30</td>
<td></td>
</tr>
<tr>
<td>$R^2_{adj}$</td>
<td></td>
<td>77.61%</td>
<td></td>
</tr>
</tbody>
</table>

Having carried out the first regression run, it will be necessary to carry out another run, this time eliminating the explanatory variable AVVOL (t-statistic = 0.02, which is less than 1.98) from the regression.

The elimination of the explanatory variable for the average volume of concrete in each load after the first run may be somewhat surprising, but in the UK the majority of fresh concrete suppliers use 6 or 8 m$^3$ truckmixers so the variation in volume per load is relatively small. What also has to be remembered is that a contractor will always try to order a full load – this is due to the fact that it is more economical.
5.9.2 Regression Run 2

For the next regression run, the explanatory variables included in the regression can be seen in Table 5.8.

<p>| Table 5.8  Explanatory variables considered in Regression Run 2 |
|--------------------------|--------------------------|</p>
<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Explanatory Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME</td>
<td>TOTVOL, YEAR, TYPE, TRUCK, START, WEATHER, PROJ</td>
</tr>
</tbody>
</table>

Table 5.9 shows the estimated partial regression coefficients and the corresponding $t$-statistics from the regression on $TIME$ for the seven explanatory variables under consideration in Run 2. As can be seen the $t$-statistics are again all relatively large and this is reflected by the $R^2_{adj}$ value for the second run of 0.7767 and the F-ratio of 175.51 shown in the ANOVA table in Table 5.10.

| Table 5.9  Estimated partial regression coefficients and the corresponding $t$-statistics from the regression on $TIME$ for the remaining seven explanatory variables – Run 2 |
|--------------------------|--------------------------|
|                      | Coefficients | $t$-Statistic |
|----------------------------|--------------------------|
| Intercept                | 205.16       | 7.51          |
| TOTVOL                   | 1.49         | 18.55         |
| YEAR                     | -8.44        | -1.80         |
| TYPE                     | -32.01       | -6.94         |
| START                    | -28.89       | -4.97         |
| WEATHER                  | -4.32        | -0.91         |
| TRUCK                    | 11.57        | 3.70          |
| PROJ                     | 16.70        | 4.60          |
Table 5.10 ANOVA statistics for regression on TIME – Run 2

<table>
<thead>
<tr>
<th></th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>7</td>
<td>4672313.08</td>
<td>667473.30</td>
<td>175.51</td>
</tr>
<tr>
<td>Residual</td>
<td>344</td>
<td>1308275.22</td>
<td>3803.13</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>351</td>
<td>5980588.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R² adj</td>
<td></td>
<td>77.67%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Following the second run it can be seen that the next explanatory variable to be eliminated will be WEATHER (t-statistic = 0.91, which is less than 1.98).

This implies that the weather did not greatly influence the pour duration on the sites under investigation. What is maybe more interesting at this point is that the next lowest t-statistic is that for time of year (t-statistic = 1.80). It has been suggested that weather and time of year may be related but interestingly, during the investigation for correlation this was not found to be the case. As the variable for weather and time of year are both dummy variables their actual value is somewhat arbitrary and so no particular conclusions can be drawn from this.

5.9.3 Regression Run 3

For regression run 3, the explanatory variables included in the regression can be seen in Table 5.11

Table 5.11 Explanatory variables considered in Regression Run 3

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Explanatory Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME</td>
<td>TOTVOL, YEAR, TYPE, TRUCK, START, PROJ</td>
</tr>
</tbody>
</table>
Table 5.12 shows the estimated partial regression coefficients and the corresponding t-statistics from the regression on TIME for the remaining six explanatory variables under consideration in Run 3. As can be seen the t-statistics are again all relatively large and this is reflected by the $R^2_{adj}$ value for the third run of 0.7769 and the F-ratio of 204.52 shown in the ANOVA table in Table 5.13.

### Table 5.12  Estimated partial regression coefficients and the corresponding t-statistics from the regression on TIME for the remaining six explanatory variables – Run 3

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>t-Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>198.84</td>
</tr>
<tr>
<td>TOTVOL</td>
<td>1.48</td>
</tr>
<tr>
<td>YEAR</td>
<td>-8.60</td>
</tr>
<tr>
<td>TYPE</td>
<td>-31.74</td>
</tr>
<tr>
<td>START</td>
<td>-29.20</td>
</tr>
<tr>
<td>TRUCK</td>
<td>11.70</td>
</tr>
<tr>
<td>PROJ</td>
<td>16.73</td>
</tr>
</tbody>
</table>

### Table 5.13  ANOVA statistics for regression on TIME – Run 3

<table>
<thead>
<tr>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>6</td>
<td>4669139.66</td>
<td>778189.94</td>
</tr>
<tr>
<td>Residual</td>
<td>345</td>
<td>1311448.64</td>
<td>3801.30</td>
</tr>
<tr>
<td>Total</td>
<td>351</td>
<td>5980588.30</td>
<td></td>
</tr>
<tr>
<td>$R^2_{adj}$</td>
<td>77.69%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Following the third run it can be seen that the next explanatory variable to be eliminated will be YEAR ($t$-statistic = 1.83, which is less than 1.98).

It is assumed that the time of year, as an explanatory variable, has had a relatively low ranking in much the same way as weather. This may be somewhat surprising as much of
the data was collected in the north of Scotland which does typically experience harsh winter conditions.

5.9.4 Regression Run 4

For regression run 4, the explanatory variables included in the regression can be seen in Table 5.14.

Table 5.14 Exploratory variables considered in Regression Run 4

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Explanatory Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME</td>
<td>TOTVOL, TYPE, TRUCK, START, PROJ</td>
</tr>
</tbody>
</table>

Table 5.15 shows the estimated partial regression coefficients and the corresponding t-statistics from the regression on TIME for the remaining five explanatory variables under consideration in regression run 4. As can be seen the t-statistics are again all relatively large and this is reflected by the $R^2_{adj}$ value for the forth run of 0.7754 and the F-ratio of 243.32 shown in the ANOVA table in Table 5.16.

Table 5.15 Estimated partial regression coefficients and the corresponding t-statistics from the regression on TIME for the remaining six explanatory variables – Run 4

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>t-Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>182.25</td>
</tr>
<tr>
<td>TOTVOL</td>
<td>1.46</td>
</tr>
<tr>
<td>TYPE</td>
<td>-31.89</td>
</tr>
<tr>
<td>START</td>
<td>-30.77</td>
</tr>
<tr>
<td>TRUCK</td>
<td>11.86</td>
</tr>
<tr>
<td>PROJ</td>
<td>15.62</td>
</tr>
</tbody>
</table>
Table 5.16 ANOVA statistics for regression on TIME – Run 4

<table>
<thead>
<tr>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>5</td>
<td>4656341.01</td>
<td>931268.20</td>
</tr>
<tr>
<td>Residual</td>
<td>346</td>
<td>1324247.29</td>
<td>3827.30</td>
</tr>
<tr>
<td>Total</td>
<td>351</td>
<td>5980588.30</td>
<td></td>
</tr>
<tr>
<td>$R^2_{adj}$</td>
<td></td>
<td>77.54%</td>
<td></td>
</tr>
</tbody>
</table>

Following regression run 4, it can be seen that the five remaining explanatory variables are deemed to be significant since they satisfy the condition that $t$ must be greater than 1.98.

5.9.5 Initial Regression Model: Discussion

This backward stepwise regression analysis has introduced the techniques used to produce a final model. In carrying out this analysis it has been highlighted that by including an exploratory variable of project it has shown that the difference between projects and different management techniques is significant and ultimately has an influence on pour duration. What does one conclude from this? Do we abandon this methodology with the conclusion that because we cannot allow for, or estimate, the explanatory variable PROJECT in any predication model such a prediction model will be either unusable or undeterminable? Or do we accept that, because of the nature of construction the project will always be significant, we should continue and see what kind of prediction model we will get.

The conclusion is, of course, to continue. We should at the very least see what kind of model we will end up with. The following points should be noted:

- Construction is a stochastic, unique and one-off undertaking. This has been an underlying fundamental of this thesis from the start and the fact that PROJECT is significant is expected. The first regression model, defined above, confirms this.
- We have to accept the limitations of the data collection exercise. Chapter 3 indicated the types of data collected and the wide range of factors at play. However, it would
be impossible to identify, observe, measure and record every single factor that is at play in this system. If this were possible we could expect that the regression model produced would be perfect. As it is the Adjusted $R^2$ value is approximately 77% which means that 23% of the variability within our data cannot be explained by the model and is, effectively, unmeasured. Some of the system variability is taken up by the dummy variable \textit{PROJECT} but, a significant proportion is not.

- The ultimate test will be whether a prediction model will be valid against a further set of data from a separate project. If the differences are acceptable then the model will be useable irrespective of whether or not \textit{PROJECT} has been used.

In the following sections the regression analysis will be carried out again without \textit{PROJECT}, as an exploratory variable and the prediction model will be validated against a separate set of data. Only the final run will be presented, though the methodology will be the same as previously used.

### 5.10 A prediction model using backward stepwise regression analysis

The regression analysis will be performed using only seven exploratory variables in the first run. As before, the aim was to conclude with a model in which all the exploratory variables have a $t$-statistic > 1.98. In order to achieve this it was necessary to carry out the regression analysis three times. Table 5.17 shows the exploratory variable eliminated after each the first two runs.

<table>
<thead>
<tr>
<th>Regression Run</th>
<th>Explanatory Variables</th>
<th>Eliminated Variable</th>
<th>$t$-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TOTVOL, YEAR, TYPE, AVVOL, START, WEATHER, TRUCK</td>
<td>WEATHER</td>
<td>0.842</td>
</tr>
<tr>
<td>2</td>
<td>TOTVOL, YEAR, TYPE, START, AVVOL, TRUCK</td>
<td>YEAR</td>
<td>1.333</td>
</tr>
</tbody>
</table>

Table 5.17 Summary of Regression Runs 1 and 2
For the final regression run, the explanatory variables included in the regression analysis can be seen in Table 5.18.

Table 5.18 Explanatory variables considered in the final Regression Run for prediction model

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Explanatory Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME</td>
<td>TOTVOL, TYPE, START, AVVOL, TRUCK</td>
</tr>
</tbody>
</table>

5.10.1 Final Prediction Regression Model

Table 5.19 shows the estimated partial regression coefficients and the corresponding t-statistics from the regression on TIME for the remaining five explanatory variables under consideration in the final regression run. As can be seen the t-statistics are again all relatively large and this is reflected by the $R^2_{adj}$ value for the final run of 0.7692 and the F-ratio of 235.05 shown in the ANOVA table in Table 5.20.

Table 5.19 Estimated partial regression coefficients and the corresponding t-statistics from the regression on TIME for the remaining three explanatory variables – Final Run

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>t-Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>169.11</td>
</tr>
<tr>
<td>TOTVOL</td>
<td>1.40</td>
</tr>
<tr>
<td>TYPE</td>
<td>-33.83</td>
</tr>
<tr>
<td>AVVOL</td>
<td>12.59</td>
</tr>
<tr>
<td>START</td>
<td>-35.73</td>
</tr>
<tr>
<td>TRUCK</td>
<td>10.44</td>
</tr>
</tbody>
</table>
### Table 5.20  ANOVA statistics for regression on TIME – Final Run

<table>
<thead>
<tr>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>5</td>
<td>4620342.44</td>
<td>924068.49</td>
</tr>
<tr>
<td>Residual</td>
<td>346</td>
<td>1360245.86</td>
<td>3931.35</td>
</tr>
<tr>
<td>Total</td>
<td>351</td>
<td>5980588.30</td>
<td></td>
</tr>
<tr>
<td>$R^2_{adj}$</td>
<td></td>
<td>76.92%</td>
<td></td>
</tr>
</tbody>
</table>

Following the final regression run, it can be seen that the five remaining explanatory variables are deemed to be significant since they satisfy the condition that $t$ must be greater than 1.98.

The final model can also be stated thus:

\[
\text{TIME} = 1.40 \text{TOTVOL} - 33.83 \text{TYPE} + 12.59 \text{AVVOL} - 35.73 \text{START} + 10.44 \text{TRUCK} + 169.11
\]

Equation 5.19

Where

- **TIME** = Total duration of concrete pour
- **TOTVOL** = Total volume of concrete in pour
- **TYPE** = Type of pour
- **AVVOL** = Average volume of concrete per load
- **START** = Start time of pour
- **TRUCK** = Number of trucks used during pour

### 5.10.2 Adequacy of Final Model

It was necessary to carry out three runs of regression before all criteria were satisfied and the model was proven to be significant. From the original set of seven explanatory variables it was necessary to only remove weather and time of year. From Table 5.20, it can be seen that the F-ratio is 235.05, which is much greater than the critical F-ratio of 2.53. It is
interesting to note also that the Adjusted $R^2$ value is 76.9% - this is only slightly less than that obtained in the previous section when PROJECT was included.

As a further indication of how the regression equation fits the data, consider the plot in Figure 5.3. When the actual TIME values are plotted against the values derived from the regression equation, a linear trend with close fit is obtained; the estimate of a point that lies on the 1:1 line is exactly equal to the observed value of time.

![Figure 5.3 Actual TIME plotted against Fitted TIME for linear regression model](image)

Although it has been concluded that there is a significant regression equation for TIME, it is important that the assumptions of the regression model are satisfied. One of the most important assumptions is that the variability of the data does not change for different levels of the response or explanatory variables. One way to check this is to carry out residual plots.

The residual $e_i$ is the difference between the observed response $y_i$ and the estimated or fitted value $\hat{y}_i$. If the constant variance assumption holds true, then residuals will follow an $N(0, \sigma^2)$ distribution and a plot of the residuals for each $i$ against the fitted values $\hat{y}_i$ should follow a random pattern, with 95% of the points lying within a $2\sigma$ horizontal band around zero.
In Figure 5.4, the residuals from the final run of the regression analysis are plotted against fitted values of the regression equation; no non-random pattern can be detected. As the mean square of the residual in the ANOVA is an estimator for $s^2$, it can be determined from Table 5.20 that most of the residuals should fall between $\pm 2039.31$ or $\pm 125.46$. It is clear from Figure 5.4 that this is indeed the case (approximately 16 points lie outside this range, or approx. 4% of the total observations) concluding that the constant variance assumption is satisfied and that the variance itself is within acceptable limits.

![Residual plot for linear regression model on TIME](image)

**Figure 5.4** Residual plot for linear regression model on TIME

### 5.11 Validation of Derived Model

No model can be considered usable until it has been adequately validated. An unvalidated model will provide solutions that are inappropriate and correct. Validation is a large topic and there are many different levels of validation that can be achieved (see Law & Kelton, 2000, Chapter 5 for a fuller discussion), but one key issue is that the appropriate level for the modelling investigation under consideration is chosen. In this case, the model needs to be Replicatively valid – that is it must be able to provide the correct answer to a set of circumstances that have happened in the past. Ultimately, a model should be Predictively
valid – can determine the correct solution for operations that have not yet taken place – but this is impractically difficult to achieve within the scope of this project.

This section will therefore present the replicative validity of the regression model when compared to two datasets: firstly against a dataset that has not been used in developing the model; and secondly against the whole dataset.

5.11.1 Validation against independent dataset

In order for this to be of practical use on construction projects it must first be validated. For the purpose of this study the regression model is validated using actual concrete pours from the Inverness Wastewater project in Scotland (29 concrete pours). As a different contractor managed the project it will be interesting to discover if the developed model will be valid and, referring to the discussion in 5.9.5, whether it was safe to remove the variable PROJECT from our model. All pours were poured using the same methods and placing procedures.

The actual pour times achieved on 29 operations observed during the study of the Inverness Wastewater project are compared to the predicted pour times using the derived regression model; these 29 comparisons can be seen in Figure 5.5. The plot reveals an interesting trend and it can be seen that, in general, the derived regression model seems to be predicting actual concrete pour durations fairly accurately. Figure 5.6, shows the plot with each pour volume taken into consideration. It appears that for smaller concrete pours (<18m³) the model appears to be over-estimating the pour duration, while conversely for larger concrete pours (>30m³) it appears to be under-estimating the duration. To consider this it is useful to look at these results in an alternative manner. Figure 5.7 shows the percentage difference between the predicted and the observed value of duration, plotted against the pour volume.
Figure 5.5  Plot showing predicted and actual pour times on project used for validation.

Figure 5.6  Plot showing predicted and actual pour times compared to volumes of concrete per pour.
The linear trendline in Figure 5.7 is suggesting that for smaller pours the model is overestimating the pour duration (a plot above the line indicates a positive percentage difference, i.e. that Predicted > Actual) although the number of points is too small to provide a robust model for this purpose – $R^2$ is only 9%. However, it also indicates a different trend which figures 5.5 and 5.6 do not immediately convey. What can be seen is that the accuracy of the estimate improves with size of pour: the larger the volume the more likely the estimate is to be closer to reality. This is an important finding, is probably intuitively true and is of some significance in the use of this model. This too warrants further investigation.

Consider point A in Figure 5.7. The volume of this pour is 24 m$^3$ which is 4 truckmixers at 6 m$^3$ each. This particular operation has an observed duration of just over 2.5 hours. During that time just small differences in the operation – such as delays to the arrival of a truckmixer or in pumping the concrete will have a greater effect on the operation’s output than that represented by point B. This second pour has a volume of 80 m$^3$ (~13 truckmixers) and a duration of nearly five hours. In other words, the smaller the pour the more sensitive it will be to small changes; the pour will take a while to settle down before a steady rhythm of
truck arrivals and depositions is built up. This point will be reinforced later when we look at the M6 project.

5.11.2 Validation against total dataset

The validation pour set from the Inverness project is just 29 datapoints, almost exactly 10% of the size of the dataset which built the model. From this, is it possible to firmly conclude that the larger the pour, the better the estimate? It can be dangerous to make conclusions about the performance of the model from the same historical dataset for which the model was built, but Figure 5.8 shows the plot of percentage difference against pour volume for all 345 datapoints, for all five projects, including the Falkirk project which was also not used in the initial model development. It shows some interesting findings:

![Graph showing percentage difference plotted against pour volume for all projects]

Figure 5.8 Percentage difference plotted against pour volume for all projects

- Firstly the trend seen in the Inverness dataset is also present: for smaller projects, the error is greatest. Pours of around 20m³ can expect to have errors of up to 60% between actual duration and predicted.
- This overall plot also confirms the suggestion from the Inverness validation set, that if the linear trend is included, we see that for smaller concrete pours the model appears to be over-estimating the pour duration, while conversely for larger
concrete pours it appears to be under-estimating the duration. The difference being that the 'break-point' is at approximately 120m³ rather than the ~24m³ seen on Inverness. Again, however, the variability in the data makes this trend unusable for predictive purposes.

- The linear trendline is encouragingly close to the x-axis which indicates that overall, the errors tend to cancel each other out. There may be over- and under-estimating within the model but, taken as a whole, this is of a low magnitude.

- Producing a plot such as Figure 5.8 allows the consideration of individual characteristics of the different projects. Again, care must be taken in drawing firm conclusions about the ability of the model as a predictive tool as using the same input as was used to develop the model initially can only indicate the historical or replicative validity of the model. Nevertheless, we immediately see that the trends differ between projects. Firstly we can see the range of pour sizes. Inverness tends to the small size (generally <150m³); Aberdeen has a range up to ~300m³; whereas the M6 project had pours in the 100 to 300 m³ bracket.

- More significant is the performance of the model for the different projects. The model was less good at predicting the actual duration for the smaller projects such as Inverness and Falkirk. Another way of looking at this is that for these projects, the pours did not run as smoothly as for the larger projects. It can be expected that in the early stages of a project, or for a project with low overall duration, the management and operational teams have not been able to establish operating conditions which lead to effective outputs. The actual outputs have a greater variability than for larger or more well established projects. This point is emphasised when considering the results for the M6 project. This project was of a much larger scale, had greater management resources and was more established by the time the data collection commenced. Concrete placing teams would be working at a more effective level and it can be seen that the general trend for smaller pours to have greater error in the estimate is not the case on this project: indeed, on the M6 the magnitude of error does not appear to change with size of pour.

- Finally, it can be seen that for the M6 project the model seems to over estimate consistently for all pour sizes. The linear trendline, not shown, is above the x-axis, i.e. actual pour durations were generally lower than predicted, or to put another way, pour productivity rates were higher than predicted. Why would this be the
case? The answer is possibly that the M6, as already stated, was a larger and more management intensive project, had been in existence for a longer period of time and therefore one would expect pour output rate to be greater than on the other projects.

5.12 Chapter Summary

This chapter looks at regression analysis and attempts to use this method of statistical analysis to further investigate the concrete delivery and placement process. The key points and findings of this investigation are given below:

- Firstly, regression analysis was explained and the key aspects of such a method of analysis were discussed.
- The regression analysis method used was multiple linear regression and in particular backward elimination, stepwise regression. This involves starting with a full set of explanatory variables in the model and eliminating ‘non-significant’ variables one at a time until all the remaining variables are ‘significant’.
- The variables to be used in the study were decided upon following consideration of what actually was observed on site and included factors that the author thought to be significant.
- The ultimate aim was to develop a model that can then be used to estimate the total duration of concrete pours on future pours. For this reason the response variable was to be total pour duration.
- The data was subjected to mathematical analysis to ensure that it was suitable for regression analysis. It was checked for outliers and multicollinearity and any occurrences were either further investigated or omitted from the dataset.
- The first regression analysis was carried out with the sole intention of discovering whether or not the explanatory variable PROJECT was significant. This was carried out to discover if different management styles on individual projects had any impact on the performance of concrete operations. Interestingly, this explanatory variable was of enough significance to be included in the final model. As the main aim was to develop a model that may be used to predict future concrete pour durations it was realised that a variable for individual projects could not be included.
A second regression analysis was carried out, without \textit{PROJECT} as a variable. The "significant" variables that remained in the final regression model were: total volume of concrete in pour, type of pour, average volume of concrete per load, start time of pour and the number of trucks used during pour. The model was found to describe approximately 77\% of the variability in the dataset.

The model was then validated using data collected on the Inverness Wastewater Treatment Works project (this data was excluded from the original data used). It appears that for smaller concrete pours (<18m$^3$) the model has a lower degree of accuracy of estimation (over- or under-estimated) than for larger concrete pours (>30m$^3$), which has a much higher accuracy. Although the validation set is relatively small, for pours <18m$^3$ the accuracy is ± 60m$^3$/h, whilst for pours >30m$^3$ the accuracy is closer to ± 20m$^3$/h.
Simulation analysis has been highlighted as a potential technique to further investigate the concrete supply and delivery process. In this chapter, the model to be investigated is defined and the key uncertainties are identified. The data collected is then represented using ranges of values with probability distribution functions. Using this data it is then possible to carry out experiments to discover how the overall process reacts to change.
Chapter 6 Simulation Model of Concrete Operations – Development and Uses

6.1 Introduction

Since Chapter 1, the concrete supply and delivery process has been subjected to various tools and techniques to help us further understand the process. It has been seen that the process is made up of several component times, which are never fixed at one value but randomly variable. This random nature allows concrete placement operations to be considered as a stochastic system, consequently rendering accurate analysis by deterministic methods difficult – if not impossible. This stochastic system can, however, be represented as a queuing system, allowing analysis by techniques such as simulation.

Queuing theory can provide estimates for output characteristics of the queue; for example, the number of customers (truckmixers) in the queue, the expected length of time the customer spends in the queue, the probability distribution of the number of customers in the queue and the amount of time the server (pump) spends idle. Whilst these values are of interest to the concrete engineer, especially utilisation factors, the productivity of the system is of major importance and this is difficult to estimate using queuing theory. Furthermore, most queuing theory solutions require estimates of the service rate, or the average number of service completions per unit time. For a fully resourced system, the service rate is merely the inverse of the service time but the server in an under resourced system will spend an unknown amount of time idle. The service rate in this instance cannot be reliably determined and, furthermore, the idle time of the server is a variable which one would like to estimate accurately. These are two reasons why queuing theory is difficult to apply to concrete placing operations and it was believed that by incorporating simulation the model would be more flexible.

Simulation is a very adaptable method for estimating the output of a system and following the advancement of computer technology it has become a very common analysis technique.
The flexibility of the technique means that a simulation model can be repeatedly analysed for different initial conditions, allowing experimentation with the real system.

6.1.1 Developments in simulation techniques in the Construction Industry

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. More recently Smith, at the University of Edinburgh, has investigated the problem of the stochastic nature of both earthmoving and concreting processes (Smith et al., 1995a, 1995b and 1996; Smith 1998 and 1999; Graham et al., 2004) using, predominantly, discrete-event simulation models. This section will continue the review presented in Chapter 2.

Early work was started by Fondahl (1960) at Stanford University using photographic techniques to analyse the effectiveness of construction operations and further developed by Teicholz (1963) and Gaarslev (1969). 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 three 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). Halpin developed a PC version of CYCLONE, MicroCYCLONE (Halpin 1990) but this seems not to have been developed further since the early 1990s.

Clemmens and Willenbrock (1978), at Pennsylvania State University, developed a computer simulation program independent of the work going on at Stanford specifically for the estimation of scraper earthmoving operations. Scrapesim used data from three construction sites to set up probability distributions for the various parts of a scraper cycle. However, the authors commented, surprisingly, that they considered the haul road condition had no significant effect on the scraper travel time and that the capacity of the scraper and the size of the load obtained were insignificant and could not in any case be accurately predicted for
estimation purposes. On the variability of travel times, the authors "discovered that those scrapers with twin engines generally travelled at a faster rate than those with a single engine." Not surprisingly perhaps, this work does not seem to have been developed further and few references to this work exist.

More recently, a very prolific researcher into 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 is, of course, not as necessary any more as the speed of computer simulation programs has increased along with computer development in the last ten years. Computer simulation run time is no longer a limiting factor in the development of simulation models. Further work was done validating the CYCLONE program using queuing theory (AbouRizk et al. 1991a) and developing techniques to fit beta distributions to activity times in simulation models (AbouRizk et al. 1991b and AbouRizk and Halpin 1992). With Gonzalez-Quevedo et al. (1993), MicroCYCLONE was compared with SLAM II, a mainly manufacturing industry based simulation package. Similar results were established thus validating MicroCYCLONE due to SLAM II's established and tested reputation. AbouRizk and Wales (1993) used the simulation techniques in a rare excursion from the more usual earthmoving applications in developing a model to estimate the impact of adverse weather on a construction programme. More recent papers from this author offer refinements of earlier work (such as considering the concept of Resouce Based Modelling) and have brought together developments over the previous 20 years to provide what he describes as a 'Unified Simulation Methodology' (Shi and AbouRizk, 1997; Hajjar and AbouRizk, 2002.)

Other workers in this field include Amr Oloufa, currently at Pennsylvania State University. Three papers (Oloufa and Crandall 1992 and Oloufa 1993a and b) cover very similar ground by first reviewing the history of simulation in construction and then developing object-orientated techniques based on CYCLONE and developed into a new package called
MODSIM. The object oriented view that a system is composed of interacting physical objects intends to 'bridge the gap' between system and model.

6.2 The first steps to simulating concrete placement operations

In order to develop a simulation model of concrete placement operations it is necessary to:

1. **Develop the model** – define the problem

2. **Identify the uncertainty** - determine which inputs in the model are uncertain, and represent those using ranges of values with probability distribution functions. Identify which result or output of the model to analyse.

3. **Analyse the model with simulation** - run the simulation to determine the range and probabilities of all possible outcomes for the outputs identified.

4. **Make a decision** – Armed with complete information from the analysis make the simulation model work for you.

6.2.1 *Develop the Model*

Until now, concrete operations have been considered as two distinct processes: the concrete batching and delivery; and pumping and placement. In order to simplify the analysis of the process, the batching and transport of concrete will not be modelled. The model will include the arrival of a truckmixer on site as a random process and the site based operation from the time at which the truckmixer enters the site, until its time of exit, see Figure 6.1. Within this period the following times need to be taken into account:

- **Interarrival time** – time between the arrival of truckmixers
- **Position time** – time to position the truckmixer at the pump
- **Pump time** – time to discharge the load from the truckmixer
6.2.2 Identify the uncertainty

As with all modelling exercises, whether physical or numerical, the main aim of this study is to represent the concreting system in a way that can be investigated practically, economically and safely. The real concreting process is a very expensive undertaking, which limits the amount by which the underlying relationships in the process can be determined. If a model of the system is valid, i.e., it represents satisfactorily the real system; results obtained via the model can be interpreted and applied to a real situation with confidence.

Within the model to be investigated, and highlighted in Figure 6.1, there are three basic uncertainties. These are times that ultimately dictate the effectiveness of any large concrete pour. They are:

1. **Interarrival time** – time between the arrival of truckmixers
2. **Position time** – time to position the truckmixer at the pump
3. **Pump time** – time to discharge the load from the truckmixer

These three time components are central to the model under investigation. All three time components identified are variable and difficult to predict in real life concrete operations.

In order to carry out a simulation using random inputs such as interarrival times, their probability distributions have to be specified. Pritsker (1997) defined probability...
distributions as “any rule which assigns a probability to each possible value of a random variable.” In this case, theoretical distributions are being used to represent the observed data, namely interarrival, position and pump times and to level any data irregularities that may have been derived from the observations.

From this study there are four main operating characteristics that can be considered:

1. Concrete pump utilisation
2. The number of truck mixers in the system at any one time
3. Number of departures, i.e. the volume of concrete being placed
4. The total operation time

6.2.3 Analyse the model with Discrete-Event simulation

‘Discrete-Event’ Simulation is a refinement of general simulation and particularly suited to the cyclic nature of construction processes. It is a well-established technique to analyse models within construction research (see, for example, Tommelien 1997 and Smith 1998). It details the system as it develops over time and its fundamental principle is to reflect the changes of the state of the system as they occur at discrete events. In this case the events would be either an arrival or a departure of a truck mixer in the system. Only these two events can effectively change the nature of the system that is represented by the state variables. In this model, these are the arrival time of the next arrival, the departure time of the next departure, the state of the placing team and equipment and the number of trucks in the queue.

There are various ways in which to carry out a discrete-event simulation analysis. For example a dedicated computer program that specifically carries out simulations for a particular model; or alternatively one can use commercial software. In this study the Microsoft Excel add-in @RISK (Palisade, 2005) was used. @RISK uses Monte Carlo simulation to carry out “what if” scenarios on specific data and it describes the risk involved with probability distributions.
6.2.4 Make a decision

Having carried out a simulation analysis of the on-site concrete placement operation it will then be possible to carry out experiments in order to discover the most efficient working characteristics. By using random inputs for interarrival, position and pump times many simulation runs can be carried out and different scenarios investigated.

6.3 Data to be used in simulation model

The simulation model will be based on all concrete pours observed by the investigator. These were first introduced in chapter 3 and are summarised in Table 6.1

<table>
<thead>
<tr>
<th>Project</th>
<th>Year of completion</th>
<th>Location</th>
<th>Number of concrete pours observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6 Thelwall Viaduct</td>
<td>1994</td>
<td>Cheshire, England</td>
<td>64</td>
</tr>
<tr>
<td>Tay Wastewater Treatment Works</td>
<td>2000</td>
<td>Dundee, Scotland</td>
<td>54</td>
</tr>
<tr>
<td>Aberdeen Wastewater Treatment Works</td>
<td>2000</td>
<td>Aberdeen, Scotland</td>
<td>175</td>
</tr>
<tr>
<td>Falkirk Millennium Link Canal</td>
<td>2002</td>
<td>Falkirk, Scotland</td>
<td>23</td>
</tr>
<tr>
<td>Inverness Wastewater Treatment Works</td>
<td>2001</td>
<td>Inverness, Scotland</td>
<td>29</td>
</tr>
</tbody>
</table>

Table 6.2 shows the statistics that have been derived from the data, giving the interarrival time (i.e. the lapsed time between truck mixer arrivals), the position time (i.e. the time the truck mixer takes to move from the queue, position itself at the hopper of the pump and prepare itself for unloading) and the pump time.
Table 6.2: Summary of the data gathered from the observed projects

<table>
<thead>
<tr>
<th></th>
<th>Interarrival time /secs</th>
<th>Position time /secs</th>
<th>Pump time /secs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1215</td>
<td>435</td>
<td>796</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1013</td>
<td>572</td>
<td>580</td>
</tr>
<tr>
<td>No. of Observations</td>
<td>4692</td>
<td>4679</td>
<td>5077</td>
</tr>
</tbody>
</table>

As with Regression Modelling, it is important that the data used as input to a Simulation model does not contain any correlation between explanatory variables. This problem, known as Multicollinearity, was investigated in Chapter three and the conclusions found there are pertinent to this chapter also. With reference to section 5.8.2, there is sufficiently low level of multicollinearity amongst the variables to not be overly concerned.

However, in the simulation modelling exercise, the explanatory variables used in the regression are not the direct input. They are still system factors, in that 'pour size' for example will affect the operation and therefore should affect the simulation output, but the direct input to the simulation is also the three time components discussed above. A question still remains as to whether there is any multicollinearity within, for instance, 'Interarrival Time'. Smith (1995) considered this possibility within similar simulation models of earthmoving operations and demonstrated that there was no significant multicollinearity between such probability distributions. This was demonstrated via use of correlation plots and scatter diagrams which require the data to be presented in the order that it was collected. Unfortunately, the data does not exist in such a form for this project and an assumption has been made, based on Smith's outcomes and the state of the raw system factors, that there is no multicollinearity within the simulation input.

The data, collated from the time studies, is used to fit a theoretical distribution using heuristic procedures or goodness-of-fit techniques. These smooth irregularities of an empirical distribution, allowing the possibility of sampling extreme values, and represents the most compact and timesaving procedure for performing simulations (Law and Kelton 2000).
The raw data were entered into a Microsoft Excel spreadsheet and the values of interest were derived from the raw data. These values were used as the input to the BestFit program, to allow the investigation of which theoretical probability distribution is a suitable representative of the concrete placing process. BestFit (Palisade, 2005) is "is a Windows program which finds the distribution that best fits your data". Part of the same family as @RISK, it is also an add-in for Excel and tests up to 27 different probability distributions in order to provide the parameters which can then be used directly in the simulation model.

6.4 Plotting PDFs against the input data

The estimated parameters of a distribution allow the probability density function to be calculated. This PDF is plotted as a function of $x$.

There are many theoretical distribution functions which could fit a set of sample data, and because of this, the goodness-of-fit between the theoretical function and data should be assessed (Maio et al., 2000). One such method is a visual assessment. To allow a visual assessment of the closeness of fit to be undertaken, the PDF plot must be placed on top of the plot of the input data histogram.

6.5 Assessment of fit

To undertake a visual assessment of the goodness-of-fit, the shape of each PDF should be compared with the shape of the histogram. The BestFit program places the plots of PDF against histogram for each distribution together, to aid the comparison process. The PDF that has the closest matching shape, should be selected and used to represent the input data in any further analysis.

Abourizk et al. (1991b) expressed the opinion that visual assessment of the fit is often the superior method of assessing the closeness-of-fit. However, visual assessment will always be subjective and prone to potential human error and therefore mathematical support for the assessment can improve confidence in the selection. BestFit includes three formal statistical tests to provide such mathematical support, they are; Chi-Squared test, Kolmogorov-
Smirnov (K-S) and Anderson-Darling (A-D) tests and brief discussions of these tests are included to provide the background for the decision on which test to use.

6.5.1 Chi-Squared test

This is perhaps the oldest goodness-of-fit test that was first proposed in 1900 by Karl Pearson. The distribution to be tested is split into \( k \) intervals and the number of observations falling into each interval is recorded; \( N_j \) is the number of observations in the \( j \)th interval. The next stage is to compute the proportion, \( p_j \) of observations that would fall into each interval of the fitted, theoretical distribution. For an observed distribution containing \( n \) observations, the test statistic is:

\[
\chi^2 = \sum_{j=1}^{k} \frac{(N_j - np_j)^2}{np_j}
\]

Equation 6.1

since \( np_j \) is the expected number of observations that should fall in the \( j \)th interval. For a perfect fit, \( \chi^2 \) would be zero and hence we reject the hypothesis that the observed distribution is a sample from the theoretical distribution if \( \chi^2 \) is too large.

6.5.2 Kolmogorov-Smirnov (K-S) test

The Kolmogorov-Smirnov (K-S) test compares the observed data with the hypothesized theoretical distribution. This test does not require the grouping of data and eliminates the problem of interval specification (this being a problem with the Chi-Square test, Maio et al., 2000). It also checks if the observed data could have originated from a theoretical distribution, with the estimated parameters (Maio et al., 2000).

\[
F_n (x) = \frac{\text{number of } X_i \text{'s } \leq x}{N} \text{ for all real numbers } x
\]

Equation 6.2

Thus, \( F_n (x) \) is a (right-continuous) step function such that
\[ F_n(X_{(i)}) = \frac{i}{n} \]  

Equation 6.3

for \( i = 1, 2, \ldots, n \). If \( F(x) \) is the fitted distribution function, a natural assessment of goodness-of-fit is a measure of the closeness between \( F_n(x) \) and \( F(x) \). The K-S test statistic \( D_n \) is simply the largest (vertical) distance between \( F_n(x) \) and \( F(x) \) for all values of \( x \) and is defined formally by:

\[ D_n = \sup_x \left\{ F_n(x) - F(x) \right\} \]  

Equation 6.4

Abourizk et al. (1991b) expressed the opinion that the K-S statistic can be used for assessing the quality of fit from various methods of statistical analysis e.g. fitting theoretical distributions, empirical distributions, etc. Abourizk et al. (1994) used the K-S test on construction process data sets.

### 6.5.3 Anderson-Darling (A-D) Test

The Anderson-Darling (A-D) test differs from the K-S test on the weight given to the tails of the distributions (Maio et al., 2000). In fact, the A-D test is designed to detect discrepancies in the tails of probability distributions (Law and Kelton, 2000).

The A-D test statistic \( A_n^2 \) is defined by:

\[ A_n^2 = n \int_{-\infty}^{\infty} \left[ F_n(x) - F(x) \right]^2 \Psi(x) \hat{f}(x) dx \]  

Equation 6.5

Thus, \( A_n^2 \) is just the weighted average of the squared differences \( \left[ F_n(x) - F(x) \right]^2 \) and the weights are the largest for \( F(x) \) close to 1 (right tail) and \( F(x) \) close to 0 (left tail).

It was suggested that the A-D test has higher power than the K-S test against many alternative distributions (Stephens, 1974). The A-D test has not, to date, been used extensively in construction-based research (Maio et al., 2000).
6.5.4 Which test to use?

All three tests have unique advantages and disadvantages. Whilst the chi-squared is widely used it does appear to have a major weakness in that there are no clear guidelines for selecting intervals, leading to discrepancies in the same input data. The K-S does not depend on the number of intervals, which makes it more powerful than the chi-squared test. A weakness of the K-S test is that it does not model tail discrepancies very well (BestFit, 1993). The A-D test is similar to the K-S test in that it does not depend on the number of intervals, but it does place more emphasis on the tail values.

Even at this stage it is very difficult to select which goodness-of-fit test to use so it is useful to look at what other researchers have used in construction based research. AbouRizk and Shi (1994) have used the K-S test, however, stated that the chi-squared can be reliably used with large data sets (AbouRizk and Halpin 1990). In earlier research, Clemmens and Willenbrock (1978) used the chi-squared test. Graham et. al. (2005 – see appendix 1) considered both the K-S and the A-D tests, considering the results together to give an overall view of the best distributions to use in a study of the same data used here. However, considering the need to determine a single distribution to take forward to the next stage of this study, and that no test that will give you the “best” results it has been decided to use the K-S test in order to avoid the problems associated with class intervals.

6.6 What is the best fit?

Computer software programs have been developed that automatically assess the goodness-of-fit of observed data to theoretical distribution functions. The program Bestfit is used in this study. Bestfit compares the observed data to 27 different distributions (Palisade, 2005). With the Bestfit program the parameters for each theoretical distribution are compared to the sample data using maximum likelihood estimators; then they are optimised and the chi-square, K-S and the A-D goodness-of-fit test statistics are calculated. The output from Bestfit is a ranked list of these probability distributions.

As suggested by Abourizk et al. (1991b) an initial test involving a visual analysis was carried out and from this it was possible to eliminate distributions with a poor fit. Table 6.3, shows
only the top four distributions which, on visual inspection, appeared to offer a fit and these have been labelled valid distributions. Each distribution was then ranked using the K-S test statistics — ranks on the other two statistics have not been shown (see section 6.5.4 above). For each of the distributions tested the lower boundary was set to zero (that is, it is impossible to have a negative time value) which immediately eliminates certain distributions.

**Table 6.3: Ranked valid distributions for the three input data sets**

<table>
<thead>
<tr>
<th>Input variable</th>
<th>Valid distributions</th>
<th>K-S rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interarrival time</td>
<td>Gamma</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Erlang</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Exponential</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Rayleigh</td>
<td>4</td>
</tr>
<tr>
<td>Position time</td>
<td>Exponential</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Erlang</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Rayleigh</td>
<td>4</td>
</tr>
<tr>
<td>Pump time</td>
<td>Inverse Gaussian</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Pearson V</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Pearson VI</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Loglogistic</td>
<td>4</td>
</tr>
</tbody>
</table>

On the basis of these results Figure 6.2 (a, b and c) can be plotted which show the optimum fitted distributions for interarrival, position and pump times. The gamma distribution is used for the interarrival, the exponential distribution for the position time and the less familiar Inverse Gaussian distribution is used for the pump time. **BestFit** also provides the parameters of these fitted distributions (Table 6.4.)

**Table 6.4: Parameters of the probability distributions of best fit.**

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Gamma</th>
<th>Exponential</th>
<th>Inverse Gaussian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>a</td>
<td>β</td>
<td>μ</td>
</tr>
<tr>
<td>Interarrival time</td>
<td>1.9482</td>
<td>632.17</td>
<td></td>
</tr>
<tr>
<td>Position time</td>
<td></td>
<td></td>
<td>434.95</td>
</tr>
<tr>
<td>Pump time</td>
<td></td>
<td></td>
<td>795.83 1589.5</td>
</tr>
</tbody>
</table>
The heart of a simulation is the generation of random variates and in this case three must be considered, the gamma, exponential and inverse Gaussian algorithms to generate the gamma, exponential and inverse Gaussian variates.

**Figure 6.2(a):** Fitted gamma distribution to interarrival time of truck mixers

**Figure 6.2(b):** Fitted exponential distribution to position time of truck mixers
6.7 Simulation of Concrete Delivery and Placement

Discrete-event simulation is a well-established technique to analyse models within construction research. It details the system as it develops over time and its fundamental principle is to reflect the changes of the state of the system as they occur at discrete-events. As indicated earlier, the events would be either an arrival or a departure of a truck mixer in the system. Only these two events can effectively change the nature of the system that is represented by the state variables. In this model, these are the arrival time of the next arrival, the departure time of the next departure, the state of the placing team and equipment and the number of trucks in the queue. The heart of a discrete-event simulation is the generation of random variates and in this case three must be considered, the gamma, exponential and inverse Gaussian algorithms to generate the gamma, exponential and inverse Gaussian variates.
6.8 Parameters of the Simulation Model

One of the drawbacks of Monte Carlo sampling is that it creates noise and in order to reduce this the experiment should be repeated many times. Crandall (1977) proved that simulation results would be accurate if a minimum of 1,000 iterations were conducted in the simulation. With this in mind the system was instructed in this study to carry out 1,500 iterations. It was also decided that 120 events are sufficient in order to represent a typically large concrete pour with 60 arrivals and 60 departures of truck mixers. This represents a pour of approximately 360m$^3$, as the average truck mixer will have a capacity of 6m$^3$. This exceeds the maximum pour in any one day recorded during data collection.

A summary of the parameters in the model is provided below:

- Event number is the number of the event that can be an arrival or departure. This is set to 120 events.
- Event type identifies the event, whether it is an arrival or a departure of truckmixer.
- Interarrival time is the time between successive arrivals of truckmixers on site.
- Position time is the time taken by a truckmixer to move from the queue, position at the concrete pump and prepare to discharge the concrete. If no queue is present, it will be the time taken by the truck mixer to position at the pump and prepare for discharging only.
- Pump time is the time required for the truckmixer to unload the completely.
- Time is the amount of time into the concrete pour.
- The status of the concrete pump, where 0 means that the pump is idle and 1 indicates that the pump is busy.
- The number of truckmixers queuing, waiting to be unloaded.
- The time of the next arrival of truckmixer
- The time of the next departure of truckmixer. If the concrete pump is idle, this is set to 9999.
- Number in system is the number of truckmixers on site.

Figure 6.3 shows a typical window from the @RISK analysis program for the model of this concrete operation, and Figure 6.3 shows a typical results window.
Figure 6.3 Analysis screen for simulation model: @RISK within Microsoft Excel
There are several operating characteristics of interest in concrete operations, however, the four operating characteristics of interest in this study are:

1. The utilisation of the concrete pump,
2. The number of truckmixers in the system,
3. Number of departures, i.e., the number of trucks that have been served, and
4. The total operation time.

These are fundamental to the success of concrete operations and being able to predict these early greatly increases the chance of the operation running smoothly. Table 6.5 shows the simulation results. The results show the concrete pump is utilised 90.83% of the time from the arrival of the first truck the departure of the last truck. The average number of truck mixers on site was found to be 4.511. The simulation provided results for 55 departures in a time of 1279 minutes.

Figure 6.4 Results summary screen for simulation model: @RISK results window
Table 6.5: Key characteristics of the simulation model

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Pump Utilisation (%)</th>
<th>Number of Truckmixers</th>
<th>Number of Departures</th>
<th>Total Time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Results</td>
<td>90.83</td>
<td>4.511</td>
<td>55</td>
<td>1279</td>
</tr>
</tbody>
</table>

A sensitivity analysis was carried out in order to find the most significant of the three inputs in the simulation model, i.e. interarrival, position and pump time. The interarrival time was found to be the most significant and therefore, by varying the interarrival time the utilisation of the concrete pump will be greatly affected and it will be possible to find the optimum rate at which truckmixers should arrive on site.

6.9.1 Truckmixer Interarrival Time

The simulation model can easily be adapted so that it is possible to vary the interarrival time. Instead of using the gamma distribution the interarrival time was replaced with times ranging from 1 to 23 minutes. The operating characteristics can be seen in Table 6.6.
### Table 6.6: Varying interarrival times in the simulation model

<table>
<thead>
<tr>
<th>Interarrival Time (minutes)</th>
<th>Number of Truckmixers</th>
<th>Number of Serviced Trucks / 120 events</th>
<th>Total Operation Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56</td>
<td>5</td>
<td>114</td>
</tr>
<tr>
<td>3</td>
<td>47</td>
<td>14</td>
<td>315</td>
</tr>
<tr>
<td>5</td>
<td>37</td>
<td>22</td>
<td>485</td>
</tr>
<tr>
<td>7</td>
<td>31</td>
<td>30</td>
<td>623</td>
</tr>
<tr>
<td>10</td>
<td>17</td>
<td>43</td>
<td>760</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>44</td>
<td>900</td>
</tr>
<tr>
<td>14</td>
<td>13</td>
<td>49</td>
<td>980</td>
</tr>
<tr>
<td>16</td>
<td>9</td>
<td>53</td>
<td>1066</td>
</tr>
<tr>
<td>17</td>
<td>5</td>
<td>56</td>
<td>1071</td>
</tr>
<tr>
<td>18</td>
<td>4</td>
<td>56</td>
<td>1137</td>
</tr>
<tr>
<td>19</td>
<td>3</td>
<td>58</td>
<td>1159</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>59</td>
<td>1200</td>
</tr>
<tr>
<td>21</td>
<td>3</td>
<td>59</td>
<td>1260</td>
</tr>
<tr>
<td>22</td>
<td>2</td>
<td>58</td>
<td>1320</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
<td>60</td>
<td>1378</td>
</tr>
</tbody>
</table>

These results can also be represented graphically and this can be seen in figures 6.5 and 6.6.
When choosing the optimum interarrival time several factors have to be considered, such as financial viability. It can be seen that having an interarrival time of 1 minute obtains
maximum utilisation of the concrete pump – but in order to have such a short interarrival time it is necessary to have 56 trucks on the job. This would not only be very costly but the chances of finding a supplier with 56 trucks available would be very unlikely. Also, for the 120 events simulated only 5 of these were departures – indicating that the majority of trucks in such an operation join the queue and simply ensure maximum utilisation of the pump. Such an operation may be a theoretical possibility but is a practical impossibility.

Generally, shorter interarrival times result in high utilisation levels of the concrete pump but this is achieved at the expense of many truckmixers being idle on site. Conversely an interarrival time of 23 minutes would allow the concrete pour to be carried out by only one truck with, consequently, the concrete pump utilisation being the lowest of all of the times. This suggests that the truckmixer could have its concrete discharged, travel to the batching plant and uplift the next load and then return to the site within 23 minutes, which would be highly unlikely – again a practical impossibility. Practically, a concrete operation will use between 2 and 8 truckmixers. Very large concrete pours may use more than 8 truckmixers but these would be rare, would need careful planning and liaison with the suppliers to ensure that such a level of resources could be maintained.

An optimum interarrival time can therefore only be defined if one of the conflicting criteria can be said to be the most important. Do we want lowest pour duration; lowest number of trucks or maximum pump utilisation? Table 6.7 suggests optimum operations based on each of these three criteria.

<table>
<thead>
<tr>
<th>Principal Criteria</th>
<th>Interarrival Time (Minutes)</th>
<th>Operation Time (Minutes)</th>
<th>Pump Utilisation (%)</th>
<th>Practical Truckmixers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest Duration</td>
<td>14</td>
<td>980</td>
<td>100</td>
<td>13</td>
</tr>
<tr>
<td>Lowest Trucks</td>
<td>22</td>
<td>1320</td>
<td>85</td>
<td>2</td>
</tr>
<tr>
<td>Highest Utilisation</td>
<td>16</td>
<td>1066</td>
<td>100</td>
<td>9</td>
</tr>
<tr>
<td>Best combination</td>
<td>19</td>
<td>1159</td>
<td>98</td>
<td>3</td>
</tr>
</tbody>
</table>
As can be seen, for a relatively high pump utilisation the number of truckmixers will be high. Reducing truckmixers reduces pump utilisation. Can we propose an optimum interarrival time, as was the aim of this exercise? This is likely to be around 19 minutes with the knowledge that some pump under-utilisation will be experienced. Further work in this area could be undertaken by considering the cost of such operations. Inroads into such an investigation have been made by Graham and Smith (2005) using the data collected for this thesis.

6.10 Chapter Summary

This chapter provides a cursory presentation of simulation, in particular Discrete-Event simulation, as applied to the concrete placing process. Simulation has been shown to be a very useful tool for planners when matching the concrete supply to site requirements. By doing this it should be possible for the contractor to concentrate on bettering performance on site without the worry of the logistics of concrete delivery. Interarrival time of trucks is an essential characteristic of concrete pours and taking this into account at an early stage in a project can greatly increase the utilisation level of the concrete placing equipment and minimise the number of trucks on site. In this study the optimum interarrival time was found to be 19 minutes resulting in a high utilisation of 98% with an average of only 3 truckmixers present on site.

In order to demonstrate this, a simulation model needed to be created and the chosen method was Discrete-Event simulation. This allows the concrete process to be modelled as it progresses through time by recreating a probable series of events – that is, those moments within the concrete placing process in which the state of the system changes. This enables key performance parameters of the operation such as resource utilisation to be determined. In order to allow this it is necessary for the component times of the process – that is the interarrival, position and pump times of the truckmixers – to be adequately modelled and this is usefully achieved using a probability distribution. This chapter has provided a succinct investigation into which distribution is the best one to use and has concluded that the gamma distribution is used for the interarrival, the exponential distribution for the position time and the less familiar inverse Gaussian distribution is used for the pump time.
Ideally, the correct distribution should be determined for each dataset and for every concrete placing model that is developed. This is a time-consuming requirement and in this chapter was undertaken using the BestFit package. It would be useful to have a single probability distribution to use and the reader is drawn to the attention of a parallel study undertaken and published by Graham and Smith as well as this author (Graham et. al. 2005 – shown in Appendix). This further study concluded that the lognormal distribution provided an ideal 'overall' distribution for all time components for all concrete placing operations.

The simulation tool used in this study was the Microsoft Excel add-in @RISK, which was found to be easy to use and should therefore present no problems for contractors to use. It can be easily manipulated to cater for many different pour sizes and operating conditions. It also allows contractors to continually improve the input data by using pours from on-going projects. Finally, simulation allows contractors to investigate the effects of altering the three inputs quickly, without great financial loss and effectively in order to find the optimum operating characteristics for specific concrete pours.
Chapter 7

Conclusions

Individual conclusions are given at the end of chapters 3 to 6 but this final chapter brings together general and specific conclusions about the work presented in this thesis as a whole. It is important also that research such as this does not simply end when the thesis is complete, and so the further work section outlines suggestions to not only continue this work but ensure that the research carried out so far is implemented successfully.
Chapter 7 Conclusions

7.1 Introduction

In the UK construction industry, concrete delivery and placement is carried out on the majority of construction projects. At present the amount of ready-mixed concrete supplied in the UK is in the region of 23 million cubic metres per year, at a cost of £1.1 billion and £1.6 billion per annum depending on which estimate one uses. This is just the material cost, which is generally considered to be approximately 40% of total costs. It follows on that the total cost of in-situ concreting operations to UK contractors could be as high as £4 billion per annum. As a topic for research, the placement of fresh concrete on UK construction sites can in no way be considered insignificant: resource 'waste' of just 1% would amount to some £40m per year.

The research project for which this thesis is a part was set up in 1999 to investigate these problems had five clear aims and objectives which were first introduced in Chapter 1 (see section 1.2). This conclusions chapter will reflect on the work presented here in the following four sections. Section 7.2 will outline the broad methodology used; Section 7.3 will revisit the original aims and objectives to conclude how and where these have been met. Section 7.4 will present and summary of the specific points that emerged from each chapter and finally, Section 7.5 will present a discussion on potential further work that can be taken forward from the ending of this project.

7.2 Discussion on research methodology

The thesis presented here is essentially a summary of the findings of the four year research project which was undertaken at the University of Edinburgh to investigate this problem. The thesis tackled the problem with a well defined methodology discussed in chapter one. This methodology covered the following areas:

- Literature Review. It is important for any research project that a clear picture of the current state of the art is investigated and presented. For this research project this was undertaken in three separate sections. Firstly, a review of the history of concrete in general was looked at, for the UK. This allowed the scale and scope of the problem to be further redefined. Secondly, possible techniques for the investigation
of what is a non-deterministic problem were looked at. Two, regression and simulation were later investigated. Thirdly, similar problems were also considered to glean how other investigators have successfully, or indeed unsuccessfully, approached this topic.

- **Data Collection.** The dataset which was collected for this project provides one of its more significant achievements. No research investigation of this nature could be undertaken without a full set of data for which models can be developed and tested. It is clearly important that these data are carefully gathered and the thesis has shown the detailed methods involved in this process and the important factors within concreting that needed to be gathered. The nature of the data is discussed and the projects from which it were obtained are detailed. In summary: 345 separate operations were either independently observed or their historical records were interrogated. This dataset has not only been of significant use for this project, but has also been used by a further 14 researchers at both the University of Edinburgh and also at the University of California, Berkeley. The appendix details the 16 articles so far published directly from the use of this dataset.

- **Lean Construction.** During the course of the literature review and the early stages of the project, an emerging philosophy for construction was identified. Lean construction has been in consideration by various research communities for just over a decade, and by some industrial organisations since the mid-nineties and it became apparent that the problem of concrete placing planning & estimation was directly aligned with the view of construction that is Lean Construction. This led to a paper presented at the 2000 conference of the International Group for Lean Construction (Dunlop & Smith 2000c, Appendix) and a journal paper later (Dunlop & Smith, 2004, Appendix). A full investigation of this concept as applied to concrete placing was undertaken to ascertain, principally, the cost, resource and other waste savings that could be made within concrete placing.

- **Regression analysis and modelling.** This tool was identified early on as a very useful way of considering the concrete placing system as it allows the non-deterministic and stochastic nature of concrete placing to be modelled in a deterministic manner. This led to an early journal paper (Dunlop & Smith, 2003, Appendix.) However, unless used correctly, regression can provide vastly erroneous results and conclusions and thus it was a vital part of this methodology that the
approach was correct. Detailed consideration of the data was important to establish which variables could be used within the model, which were highly correlated and unable to be used, and which were of the greatest significance to the process. Two models were produced, which were successfully validated against a test dataset.

- **Simulation Modelling.** Again, like regression, this was identified early on as a tool which could be successfully applied to the concrete placing process when considered as a cyclic process. Discrete-event simulation has been used by a number of researchers to model this & similar processes and a broad investigation was conducted using the commercial software @RISK to consider the effectiveness of the method and its use in undertaking sensitivity analyses. The paper presented at the 2002 conference of the Association of Researchers in Construction Management covers this investigation (Dunlop & Smith, 2002, Appendix).

### 7.3 Aims and objectives revisited

In Chapter 1, the five original aims and objectives of this work were introduced. It is important that now, at the end of the work, these objectives are considered in the light of what research actually took place, and conclusions made as to whether the objectives were met.

The five original objectives and their discussions follow:

1. **To investigate and provide a better understanding of cyclic construction processes with particular reference to concreting operations.** This is essentially the reason for the work existing in the first place and is the general theme running through the entire thesis. The objective is satisfied by undertaking the following four objectives but some comments should be made. During the time spent observing concrete operations an understanding of the activities was gained which was not held by the management of those operations themselves. For example, the contractors management did not consider the productivity of an operation and could certainly not make an informed estimate of the output that was being achieved. The differences between base, wall and column pours may have been intuitively felt but could not be expressed in terms of the differences in duration and productivity. Away from the projects themselves, it became apparent that the cyclic concreting process could be understood on a variety of levels. At the micro level, the process...
can be described as a classic queuing system and this led successfully to the techniques of analysis investigated. At the macro level, the process could be looked at in the context of lean construction, this time with mixed results.

2. **To study live construction projects to gain data of cyclic processes.** This is possibly the research project’s greatest asset. In total, four live projects were observed for a period totalling some ten months, and a fifth project was also investigated by way of data from records. This provided a dataset of 345 concrete pours which has not only enabled the work in this thesis to be carried out but, as discussed above, enabled a further 14 researchers to carry out their work leading, at present, to a total of 16 publications.

3. **To examine methods to assist in the planning and estimation of cyclic construction processes.** From a literature review carried out early in the project, six methods were identified as having potential use in this respect. These were fully investigated and two (lean construction and concurrent engineering) led to conference papers early on in the project (2000 and 2001 respectively, details in the appendix). These two methods, as a result of these conferences, were felt to be more philosophy than tools and so were not developed further into models or systems. Of the remaining fours, queuing theory was used as a representation of the concreting system, neural networks were not pursued further and simulation and regression modelling were developed into full models.

4. **To examine systems which enable construction engineering organisations to better manage cyclic construction processes, in terms of the efficiency and effectiveness of resources; and**

5. **To provide systems which ultimately minimise the costs, in financial, material and human effort contexts, and maximise the productivity of concrete placing operations.** Objectives four and five were essentially the same objective but have been kept in their original separate form as detailed in the original research proposal. Essentially, the objective here is to produce systems which aid in the management of concrete placing operations and this can be concluded as successful. The word ‘systems’ should more accurately be referred to as ‘models’ and this is the term used throughout this thesis. Two models were produced: simulation and regression, and of these regression can be considered to be the most successful in
terms of its portability to 'construction engineering organisations'. The final regression model produced can be directly taken and used in the planning and estimation of concreting operations which should lead to better management of efficiency, effectiveness, productivity and resources. It should be pointed out, though, that at this stage no such organisation has actively taken up this tool and thus further work is needed in the area of model development, validation and usage, a comment made in section 7.5

7.4 Specific conclusions

Specific outcomes and points relating to each phase of this methodology are presented in the body of the thesis. These are now summarised in order to provide an overview of this project's findings.

1. The delivery of fresh ready mixed concrete to a construction site and the subsequent placement of it represents two different systems: one on the construction site and the other at the batching plant.

2. Current practices of concrete delivery and placement in the UK were investigated and the most relevant tools and techniques in order to further study the process were found to be:
   - Simulation analysis,
   - Regression analysis,
   - Queuing theory,
   - Lean construction,
   - Concurrent Engineering, and
   - Neural Networks.

3. Five construction projects were studied for an overall period of more than twelve months. From this 345 concrete operations (or pours), of varying size, were investigated in detail in a data gathering exercise providing the dataset used in the development of the subsequent models. This dataset has been used not only in this research project but additionally in approximately 8 further research projects of differing sizes and complexities.
Concrete pours are generally wall, column or base pours. Each of these has individual characteristics and requirements. Generally the concrete in column and wall pours will be placed at a slower rate than for base pours.

The productivities achieved on the five sites under investigation varied significantly. The average for the 345 concrete pours studied with an average pour size of $89.27 \text{m}^3$ was $15.84 \text{m}^3/\text{hr}$. The average measured productivity for base and slab pours was $21.27 \text{m}^3/\text{hr}$ and the average measured productivity for column and wall pours was $10.38 \text{m}^3/\text{hr}$.

The concept of waste, in the form of truckmixer and concrete pump idleness, together with any labour resource wastage, was highlighted. For all concrete pours in the dataset, on average, truckmixers were idle for 25% of the total pour duration and the concrete pump was idle for 16% of the total pour duration. The cost associated with these delays is, of course, very difficult to determine but a very approximate estimate indicates that the cost of resources associated with these idle times come to some £23,500. This is just for the operations observed in this project, which only constitute a small proportion of all operations for these projects.

A key factor promoting the productivity of a concrete pour is timely supply of ready mixed concrete to site. Illustrating the difficulty, for only 36 of the 345 pours studied (approx. 10%), as stated above, was an uninterrupted supply of concrete achieved. This is a fundamental part of the problem studied in this thesis and a central tenet of the lean construction philosophy later investigated. Concrete placing is a conversion process, taking the flow of material and converting into a value added product. Interrupt that flow, as was experienced in the majority of pours, and an effective and efficient operation is not achieved.

Figure 3.19 shows a “cost effective zone” that all concrete pours should be striving to fall within. This in effect is an arbitrary zone showing a good match of supply to requirement as a truckmixer hour provision of between 100 and 150% of pour time and an interruption in supply of not more than 10% of pour time. For the pours studied only 15% of the 345 pours lie within this zone.

A number of principles have been developed for flow design and improvement. The implementation of these principles are key to the improvement of the efficiency of these flow processes:
• Reduce the share of non-value-adding activities
• Increase output value through systematic consideration of customer requirements
• Reduce variability
• Reduce the cycle time
• Simplify by minimising the number of steps, parts and linkages
• Increase output flexibility
• Increase process transparency
• Focus control on complete process
• Build continuous improvement into the process
• Balance flow improvement with conversion improvement
• Benchmark

10. Reducing the share of non-value-adding activities is at the heart of Lean Construction; for the concrete delivery and placement process under investigation it was shown that managing the variability within the process and reducing the cycle time went some way to improving the overall process.

11. Variability and waste within the concrete delivery and placement process were identified and recommendations were made to both improve them and ultimately eliminate them. The whole process was simplified, eliminating the inherent waste, and two distinct models – one at the concrete batching plant and one at the concrete’s final destination (e.g. construction site) – were developed. By simplifying the overall process, it was possible to highlight and control the flow activities and concentrate on making the conversion activities more efficient.

12. The regression analysis method used was multiple linear regression and in particular backward elimination, stepwise regression. This involved starting with a full set of explanatory variables in the model and eliminating ‘non-significant’ variables one at a time until all the remaining variables are ‘significant’.

13. By carrying out a regression analysis that included a variable representing the different projects studied it was discovered that different management styles on individual projects had any impact on the performance of concrete operations.

14. The ‘significant’ variables that remained in the final regression model were: total volume of concrete in pour, type of pour, average volume of concrete per load, start time
of pour and the number of trucks used during pour. The model was found to describe approximately 77% of the variability in the dataset.

15. The model was then validated using data collected on the Inverness Wastewater Treatment Works project (this data was excluded from the original data used). It appears that for smaller concrete pours (<18m³) the model appears to be over-estimating the pour duration, while conversely for larger concrete pours (>30m³) it appears to be under-estimating the duration.

16. Simulation was shown to be a very useful tool for planners when matching the concrete supply to site requirements. A developed model would allow contractors to concentrate on bettering performance on site without the worry of the logistics of concrete delivery.

17. The truckmixer interarrival time is an essential characteristic of concrete pours and taking this into account at an early stage in a project can greatly increase the utilisation level of the concrete placing equipment and minimise the number of trucks on site. In this study the optimum interarrival time was found to be 19 minutes resulting in a high utilisation of 98% with an average of only 3 truckmixers present on site.

18. The concrete process was modelled as it progressed through time by recreating a probable series of events – that is, those moments within the concrete placing process in which the state of the system changes. This process is known as Discrete-Event Simulation and it enabled key performance parameters of the operation such as resource utilisation to be determined. In order to allow this it was necessary for the component times of the process – that is the interarrival, position and pump times of the truckmixers – to be adequately modelled and this was usefully achieved using a probability distribution.

19. The \textit{gamma} distribution was used for the interarrival, the \textit{exponential} distribution for the position time and the less familiar \textit{inverse Gaussian} distribution was used for the pump time.

20. The development of such a simulation model allows contractors to investigate the effects of altering the three inputs quickly, without great financial loss and effectively in order to find the optimum operating characteristics for specific concrete pours.
7.5 Recommendations for Further Work

In actuality, recommendations that can be made here have, to a certain extent, already been implemented and undertaken. This investigator has had the luxury of having this research project overlap with those of subsequent investigators, and has been able to see early outcomes of those projects.

Recommendations fall into two main areas: Lean Construction and Model Development.

7.5.1 Lean Construction

- This has been found to be a vast area with a number of very enthusiastic researchers around the world. It is still an emerging discipline and this thesis has shown that the concrete placing process is ideal for study in this way. It is recommended that further work be done in this area by expanding the literature review and considering the work of key players such as Ballard and Tommelein at Berkeley, Howell of the Lean Construction Institute and Koskela, currently at Salford.

- Further, work of this nature needs to have real construction projects from which data can be gathered and models and tools implemented. Work should be undertaken to gather industrial partners willing to partake in such an exercise and find other collaborating researchers investigating the same area. It is pleasing to report that Graham, who at the time of writing is undertaking a PhD programme at the University of Edinburgh, has made some progress in this area by collaborating with Tommelein and Ballard at Berkeley and with Choo of Strategic Project Solutions, an organisation investigating lean construction techniques being implemented at Heathrow Terminal 5.

7.5.2 Model Development

- A big area for further work is to consider further the validity of the models developed. At this stage the two types of model developed can be considered historically valid, with the regression model shown to be partly predicatively valid. If such models are to be accepted as credible tools for the planning and estimation of concreting operations then they will need to be tested on future operations and this will require the cooperation of industrial partners. In addition, validity may be increased by the consideration of alternative analysis tools.
In this thesis two main analysis tools have been considered: multiple linear regression analysis and discrete-event simulation. A far larger toolbox than this exists and it is recommended that future work consider these. Examples include Genetic Algorithms, Linear Programming, Petri Nets, Case Based Reasoning, Fuzzy Set Analysis and Artificial Neural Networks. These tools will ideally be tested with expanded datasets, even though this investigator is very pleased to have had the dataset collected initially for this project used subsequently. It is further pleasing to report that this investigator's successor, Mr Darren Graham, as well as a number of honours students at the University of Edinburgh, have already had success in considering Case Based Reasoning, Artificial Neural Networks and, to a lesser extent, Fuzzy Set Analysis. Some outcomes from this work can be seen in part 2 of the Appendix.
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Appendix

Published articles arising from this research project

The research presented in this thesis is the culmination of over four years of investigation and during that time nine articles have been prepared and published directly from the results of the data collection and subsequent analysis. These papers are presented here. There are also an additional seven articles which have indirectly arisen through separate investigation by others on the dataset collected as part of this research.
Appendix: Published Papers

A key part of the methodology within the research presented in this thesis was that the work should be published as it was carried out. This could be considered to have been a successful undertaking as nine separate articles have been published between 2000 and 2005, in a variety of locations: postgraduate workshop, international refereed conferences, and international peer-reviewed, ISI listed journals.

These papers are listed below and are reprinted in full in the following pages. Note that for many of these papers the copyright rests with the publisher and it is confirmed that this has been obtained. It is also confirmed that the permission of any joint authors has been obtained.

Additional Published Work

The following papers have all arisen out of separate investigations at the University of Edinburgh that have used the dataset that arose as a result of this research and is detailed in Chapter 3. These investigations and the papers that arose from them could not have taken place without this dataset and as it is an integral part of this research and this thesis they are listed as having relevance (General Postgraduate Degree Regulation 47.11, University of Edinburgh).

Lognormal Distribution Provides an Optimum Representation of the Concrete Delivery and Placement Process

L. Darren Graham¹; Simon D. Smith²; and Paul Dunlop³

Abstract: The process of concrete supply and delivery exhibits traits of random nature, which render control arduous. This random nature allows concrete placement operations to be considered as a stochastic system and therefore cannot be analyzed by deterministic techniques. In modeling the process realistically, it may be necessary to recreate the variability through fitting a sufficiently flexible theoretical probability distribution to observed data. There is a significant body of work relating to the probability distributions which represent general construction activities. However, there is a lack of literature aimed at determining the optimum representative of the concrete placement process. Therefore, the aim of this paper is to identify a sufficiently flexible representative of this process. To this end, construction data were collected from a number of concrete pours in Scotland, U.K. To identify a suitable distribution in this context, a computer package, PDFit, is presented. It is founded upon the production of probability density functions of select theoretical probability distributions plotted against the histogram of the input data. The principal method of assessment is a visual comparison of the shape of the probability density function and the input data histogram. This paper presents the lognormal distribution as a sufficiently flexible theoretical probability distribution to represent the concrete placing process.

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CE Database subject headings: Concrete placing; Probability distribution; Probability density function; Stochastic processes; United Kingdom.

Introduction

The process of concrete supply and delivery to a construction site commences at a batching plant, when a truck mixer is supplied with a stipulated volume of fresh concrete. On arrival at site, the truck mixer enters "service" (if no other truck mixers are present) or joins the back of a queue of waiting truck mixers. Service requires the maneuvering of the truck into position and discharging its load into the hopper of the pump. Subsequently, the concrete is relayed into the prepared formwork. The empty truck is then washed out in a preassembled area. When clean, it joins the backcycle and returns to the batching plant.

If the process were ideal, the rate at which truck mixers arrive, position, and have their load discharged would be constant. It would then be possible to estimate deterministically the time between arrivals (interarrival time) of the trucks, to avoid queuing and underutilization of the plant. However, the process of concrete supply and delivery exhibits traits of random nature, which render control arduous. This random nature allows concrete placement operations to be considered as a stochastic system, consequently prohibiting accurate analysis by deterministic methods. This stochastic system can however be represented as a queuing system, allowing analysis by techniques such as computer simulation, neural networks, queuing theory, and regression analysis.

The concrete supply and delivery process can be considered as two separate processes: Batching and delivery; and pump and placement. To simplify the analysis of this process, the modeler could "ignore" the batching and transport of the concrete and simply model the arrival of a truck mixer on site as a random process and considering the whole operation from the time at which the truck mixer enters the site, until its time of exit. Within this period, the following factors must be considered: interarrival time (time between the arrival of trucks), position time (time to position the truck at the pump), and pump time (time to discharge the load from the truck-mixer).

To ensure the production of a realistic queuing system model, it is necessary to recreate the variability of the concrete placing system. It is desirable to be able to represent this variability through probability distributions of sufficient flexibility. There are two methods to achieve this. They are:

- Using the observed data to define an empirical distribution, and
- Fitting a theoretical distribution to the observed data

The latter is preferable as it allows the modeler to analyze the system for situations outside the norm. This is essential when undertaking an experimental analysis.
Probability distributions have been used by numerous researchers in the modeling of construction activities. In the study of earthmoving operations, Al-Masri (1985) used the lognormal distribution, Farid and Aziz (1993) used the beta distribution, and Spea et al. (1964) used the exponential Erlang distribution, Lemmens and Willenbrock (1978) used the Erlang and normal distributions, Farid and Koning (1994) used the beta distribution, and Smith et al. (1996) used the Erlang distribution and Carmichael (1987) used the Erlang distribution. Abourizk et al. (1994) fitted the beta distribution to all construction activities, Abourizk and Halpin (1992) used the beta distribution to model input data for construction simulation, and Maio et al. (2000) carried out an extensive survey of the distributions which represent construction data. Finally, Smith (1998, 1999) experimented with the applicability of the Erlang, Weibull, gamma, and beta distributions to concrete placement data.

It is essential in simulation applications that the selected distribution to model the collected data truly reflects the properties of the data (Abourizk and Halpin 1990). Therefore, it is of concern that there is a lack of literature aimed at determining if the probability distributions deemed appropriate for use in construction activities, generally, are suitable for use as representatives of the concrete placement process. Consequently, the aim of this paper is to determine a probability distribution, which is sufficiently flexible to represent the concrete placement process.

A primary conclusion of this paper is that the lognormal distribution is a sufficiently flexible theoretical distribution to represent the concrete placing process. The selected distribution can be used to create random variates for use in a simulation model of the process. However, the evaluation of this paper depends on the validation of the methodology to which the distribution was fitted. On validation, the methodology can be used to yield estimating and planning information, which could improve the performance of civil engineering construction companies in actual concrete placement operations.

**PDFit Program**

This paper presents a new computer application, PDFit, which was developed using Visual Basic for Applications programming language, embedded into the Microsoft Excel spreadsheet package. It is based on the production of probability density functions (PDFD) of select theoretical probability distributions plotted against the histogram of the input data. The distributions that have been utilized in PDFit are the uniform, normal, lognormal, exponential, Weibull, gamma, and beta. The mathematical forms of these distributions are provided by Wal and Kelton (1991). Actual construction data were collected from large concrete pours on four construction projects in Scotland, U.K. This data provided the input to the PDFit program. The principal method of assessment was a visual comparison of the shape of the PDF and the underlying histogram. However, formal statistical methods are employed in PDFit to provide mathematical exposure for the visual assessment.

The steps involved in PDFit to fit theoretical probability distributions to the input data are:
1. Create an input data histogram,
2. Estimate parameters,
3. Plot PDF(s) against input data histogram,
4. Visually assess the fit, and
5. Conduct goodness-of-fit tests.

**Data Collection**

The raw data collected for this investigation were the pour date, weather, target slump, location of pour, batch time, arrival time, start and completion time of pumping, batch quantity, concrete slump, truck wait time, and operation inactive time.

The data were collected from two major construction projects in the United Kingdom discussed below.

**Project 1. Aberdeenshire Wastewater Treatment Plant**

The Aberdeenshire wastewater treatment plant constitutes the design, build, operate, and maintenance of four treatment plants. These will serve 250,000 customers in Aberdeen, Stonehaven, Peterhead, and Fraserburgh in the north of Scotland, under a 30-year concession. The financing of this £80 million project has been organized under the United Kingdom government's Private Finance Initiative. The data collected were from the Aberdeen, Fraserburgh, and Peterhead sections of the project. A fourth section, Stonehaven, was not included as construction activities had not commenced during the period of data collection.

From the Aberdeen site, 154 concrete pours were sampled. The volume of the samples ranged from 12 to 294 m³, with an average of 57.1 m³. The average number of truckloads and the average delivery volume per pour were 7 and 7.33 m³, respectively. From the Fraserburgh site, 20 concrete pours were sampled. The volume of the samples ranged from 32 to 315 m³, with an average of 125.9 m³. The average number of truckloads and the average delivery volume per pour were 19 and 7.16 m³, respectively. From the Peterhead site, 10 concrete pours were sampled. The volume of the samples ranged from 18 to 294 m³, with an average 143.9 m³. The average number of truckloads and the average delivery volume per pour were 19 and 7.2 m³, respectively.

**Project 2. Tay Wastewater Project**

The aim of this project is to design, procure, construct, commission, and performance test a wastewater treatment plant near Dundee, U.K. The plant will serve customers in Dundee, Carnoustie, and Arbroath. The financing of the project is being organized under the United Kingdom government's Private–Public Partnership Initiative.

The data collected were from the Arbroath site, where 48 concrete pours were sampled. The volume of the samples ranged from 12 to 180 m³, with an average of 76.4 m³. The average number of truckloads and the average delivery volume per pour were 12 and 5.89 m³, respectively. In total, 232 pours were sampled and used in this investigation.

Upon completion of data collection, the raw data were entered into a Microsoft Excel spreadsheet and the values of interest were derived from the raw data (an example is shown in Table 1). These values were used as the input to the PDFit program, to allow the investigation of which theoretical probability distribution is a suitable representative of the concrete placing process.

**Fitting Distributions**

**Creating an Input Data Histogram**

To make a histogram, the range of values covered by the data is broken up into \( k \) disjoint adjacent intervals \([b_0, b_1], \ldots, b_k\).
their width with using histograms. Most irksome is the absence of a definitive further, it is easy to visually judge the closeness of provide a readily interpreted visual synopsis of the data. Further-
distributions on the basis of shape alone (location and scale dif-
fine them (Smith 1998). There are a number of methods which
consider only MLEs further, as this method has been generally acknowledged to provide the most satisfactory estimates (Law and Kelton 1991).
The likelihood function is
\[
L(\theta) = f_1(X_1) \cdot f_2(X_2) \cdots f_k(X_k)
\]
The MLE is defined to be the value of \( \theta \) that maximizes \( L(\theta) \) over all permissible values of \( \theta \).
Although MLEs are widely regarded as the method which provides the most satisfactory parameter estimates, there has been criticism in recent research literature. Abourizk et al. (1994) criticized the use of the MLE method because it requires prior knowledge of the endpoints of the beta distribution, and that this information is not commonly known in construction processes. Further criticism was that this method is extremely sensitive to the values of \( L \) and \( U \). Abourizk et al. (1994) recommended that the method should only be used by a simulation analyst with extensive knowledge of the properties of the underlying distribution to verify the endpoints.

### Plotting Probability Density Functions Against the Input Data Histogram

The estimated parameters of a distribution allow the PDF to be calculated. This PDF is plotted as a function of \( x \).

There are many theoretical distribution functions which could fit a set of sample data, and because of this, the goodness of fit between the theoretical probabilities and data should be assessed (Maio et al. 2000). One such method is a visual assessment. To allow a visual assessment of the closeness of fit to be undertaken, the PDF plot must be placed on top of the plot of the input data histogram. Fig. 1 shows a plot of the select PDFs against the interarrival time data histogram.

### Assessment of Fit

To undertake a visual assessment of the goodness of fit, the shape of each PDF should be compared with the shape of the histogram.
The PDFit program places the plots of the PDF against the histogram for each distribution together, to aid the comparison process. The PDF that has the closest matching shape, should be selected and used to represent the input data in any further analysis.

Abourizk et al. (1991) expressed the opinion that visual assessment of the fit is often the superior method of assessing the closeness of fit. However, visual assessment will always be subjective and prone to potential human error and therefore mathematical support for the assessment can improve confidence in the selection. PDFit includes two formal statistical tests to provide such mathematical support, they are: Kolmogorov–Smirnov
of statistical analysis, e.g., fitting theoretical distributions, empirically can be used for assessing the quality of fit from various methods. Abourizk et al. (1991) expressed the opinion that the theoretical distribution, with the estimated parameters (Maio et al. 2000). It also checks if the observed data could have originated from a theoretical distribution, with the estimated parameters (Maio et al. 2000).

\[ F_a(x) = \frac{\text{number of } X_i \leq x}{N} \quad \text{for all real numbers } x \]  

(3)

Thus, \( F_a(x) \) is a (right-continuous) step function such that

\[ \frac{1}{n} \sum_{i=1}^{n} \mathbf{1}(X_i \leq x) = F_a(x) \]  

(4)

The K–S test statistic \( D_n \) is simply the largest (vertical) distance between \( F_a(x) \) and \( F(x) \) for all values of \( x \) and is defined formally by

\[ D_n = \sup \left\{ |F_a(x) - F(x)| \right\} \]  

(5)

Abourizk et al. (1991) expressed the opinion that the K–S statistic can be used for assessing the quality of fit from various methods of statistical analysis, e.g., fitting theoretical distributions, empirical distributions, etc. Abourizk et al. (1994) used the K–S test on construction process data sets.

Kolmogorov–Smirnov (K–S) Test

The K–S test compares the observed data with the hypothesized theoretical distribution. This test does not require the grouping of data and eliminates the problem of interval specification (this being a problem with the Chi-square test, Maio et al. 2000). It also checks if the observed data could have originated from a theoretical distribution, with the estimated parameters (Maio et al. 2000).

\[ A_n^2 = n \int_{-\infty}^{\infty} \left[ F_a(x) - \hat{F}(x) \right]^2 \Psi(x)^2 \hat{F}(x) dx \]  

(6)

Thus, \( A_n^2 \) is just the weighted average of the squared differences \( \left[ F_a(x) - \hat{F}(x) \right]^2 \) and the weights are the largest for \( \hat{F}(x) \) close to 1 (right tail) and \( \hat{F}(x) \) close to 0 (left tail).

It was suggested that the A–D test has higher power than the K–S test against many alternative distributions (Stephens 1974). The A–D test has not, to date, been used extensively in construction-based research (Maio et al. 2000).

Experimental Analysis and Results

The aim of the experimental analysis was to identify a theoretical probability distribution that is representative of the concrete placement process. To achieve this aim, two experiments were devised.

**Experiment One: Combined Concrete Pours**

The differences in the experiments lie in the data which were selected to be inputted into PDFit. Experiment 1 involved combining the data which were gathered from real concrete pours, into large data sets. The main factors of interest, the interarrival, position, and pump times constituted 2,180, 2,177, and 2,364 time durations, respectively. Although these data sets would prove unrepresentative of an individual concrete pour, the results of Experiment One will provide a general overview of the concrete placement process.

**Interarrival Time Results**

The comparison plot for the lognormal, exponential, Weibull, gamma, and beta distributions are shown in Figs. 1(a–e). The smoothest histogram contained 10 class intervals. The histogram of the input data is positively skewed (to the right) and has a right tail which swiftly falls in probability. Due to the nature of this histogram, the uniform and normal PDFs are ruled out immediately from further consideration, as they are of a symmetrical disposition. The remaining distributions all bear some resemblance to the underlying histogram and require a more detailed inspection. Although the Weibull [see Fig. 1(c)], gamma [see Fig. 1(d)], and beta [see Fig. 1(e)] PDFs skew in the correct manner in relation to the underlying histogram, their right tails fall with a shallow gradient compared with that of the histogram. This results in an overestimation of the input data. The exponential PDF [see Fig. 1(b)] is ruled out because it provides an underestimation of the input data, which are most prevalent in the tail of the distribution. The importance of achieving an accurate representation of the input data when simulating a process cannot be overemphasized. Therefore, any over- or underestimation will reduce the accuracy of the analysis.

Therefore, the lognormal distribution [see Fig. 1(a)] is considered to be the optimal representative of interarrival time, subject to results of goodness-of-fit tests. The results of the K–S and A–D tests (see Table 2) provide statistical support for the conclusion drawn in the visual inspection, that the lognormal distribution best represents the interarrival time data.

**Position Time Results**

The comparison plots for select distributions are shown in Figs. 2(a–d). The smoothest histogram contained 12 class intervals. The underlying histogram is significantly skewed to the right, which will result in any symmetrical distributions (i.e., the uniform and normal) being considered unrepresentative of the input data. The underlying histogram has a right tail which falls in an exponential manner. This nature allows the exclusion of the beta distribution, as it provides an inferior fit compared with the remaining distributions. The selection is now between the lognormal [see Fig. 2(a)], exponential [see Fig. 2(b)], Weibull [see Fig. 2(c)], and gamma [see Fig. 2(d)] distributions.

Upon close inspection of the remaining curves, the lognormal distribution appears to provide the optimum representation of the input data. The exponential, Weibull, and gamma distributions all attain a similar shape to the underlying histogram, but underestimate the input data, notably in the tail of the distribution. The statistical test (see Table 2) results support the visual assessment, ranking highly the exponential and Weibull PDFs. The K–S test
results (see Table 2) contrast with those of the A–D test, regarding the ranking of the lognormal and gamma distributions.

**Pump Time Results**
Visual assessment was carried out for pump time data in the same manner, as that for interarrival and position times. The conclusions drawn by the writer were that the lognormal and exponential PDFs provide acceptable representation of the input data. However, it was felt that the lognormal provided better estimates of the shorter and longer pump times. The formal statistical tests (see Table 2) confirmed that the lognormal was the optimal distribution to represent pump times.

**Discussion on Experiment One**
Here is a discrepancy between the results of the visual assessment and K–S test, for interarrival and position times. For position time, the exponential distribution is favored by the K–S test, but can clearly be seen by visual means, to provide an inferior fit in the tail of the distribution. Therefore, the A–D test result is probably more significant in this case, as the test is designed to detect discrepancies in the tails of distributions (Law and Kelton 1991). Furthermore, the A–D test is reported to have higher power than the K–S test against many alternative distributions (Stephens 1974).

Through consideration of the results of Experiment One, for each of the duration types, it can be seen that the lognormal distribution is best at representing the concrete placement process. However, the data sets used in this experiment were large and would prove unrepresentative of individual concrete pours, therefore, a second experiment has been undertaken to investigate if the lognormal distribution is representative of individual pours.

**Table 2. Results for Experiment One: Distributions Ranked in Ascending Order**

<table>
<thead>
<tr>
<th>Test</th>
<th>Uniform</th>
<th>Normal</th>
<th>Lognormal</th>
<th>Exponential</th>
<th>Weibull</th>
<th>Gamma</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interarrival</td>
<td>7</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Potential time</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Pump time</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Anderson–Darling</td>
<td>7</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Interarrival</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Position time</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

**Fig. 2.** Lognormal, exponential, Weibull, and gamma probability density functions for position time
Experiment Two: Individual Concrete Pours

The objective of Experiment Two was to determine if the result of Experiment One is representative of individual concrete pours, in general. To achieve this objective the data from 232 concrete pours were inputted individually into PDFIt. The results from the computer program were assessed in the same manner as in Experiment One: Visual assessment, K-S, and A-D tests.

Interarrival Time Results

A visual inspection of the 232 data sets revealed that the lognormal distribution is the most representative of the input data (see Table 3 and Fig. 3). The underlying histogram, in general, had a strong positive skew (to the right) and the lognormal and gamma distributions are good representatives. This view is supported by the results of the visual assessments, as the lognormal and gamma distribution were ranked first in 42.3 and 23.4% of cases, respectively (see Table 3 and Fig. 3).

The statistical tests provide some support for the results of the visual assessment. The K-S test found the lognormal and gamma distributions to optimally represent the input data in a number of cases (see Table 3). However, it was found that the beta was the most representative distribution, but graphically this proved to be untrue. The A-D test found the lognormal distribution to be the optimum representative of the interarrival time data (see Table 3).

Position Time Results

The underlying histograms, in general, displayed either a strong positive (to the right) or negative (to the left) skew. This nature resulted in the lognormal, gamma, and beta distributions representing the input data in most cases (see Table 3 and Fig. 4).

Through visual assessment the lognormal distribution was found to optimally represent the position time data, having been ranked first in 42.3% of cases (see Table 3 and Fig. 4). This result was supported by the A-D test result, which ranked the lognormal distribution first in 55.4% of cases (see Table 3). The beta distr-
A histogram with a positive skew was visually judged to be best represented by either the lognormal or gamma distributions. These distributions are characterized by a sharp peak close to the origin of the distribution, therefore replicating the character of the skew. The lognormal distribution was visually judged to represent a larger percentage of the pours (see Table 3) than the gamma distribution. Generally, this was the due to the lognormal providing a superior fit in the tail of the distribution. This conclusion is supported by the results of the A-D test. The A-D test identifies divergence in the tails of distributions. The underlying histograms which demonstrated a negative skew were best presented by the beta distribution.

The K-S test results provided strong support for the use of the beta distribution, but this contradicts the results of the other appraisal methods. A similar conclusion to that of Experiment One can be drawn that the A-D test should take precedence over the K-S test, as it reported to have a higher power than the K-S test against many alternative distributions.

Discussion and Conclusions

As previously discussed, the process of concrete supply and delivery demonstrates random qualities, which make planning, estimation, and control difficult. These traits allow concrete placement operations to be considered as a stochastic system and thus prohibits accurate analysis by deterministic methods. However, the process can be represented as a queuing system allowing analysis by nondeterministic techniques such as simulation.

The variability of the concrete placement process must be recreated through fitting a theoretical probability distribution to observed data. It is essential that the selected distribution truly reflects the properties of the input data.

Data from real construction sites in the United Kingdom were collected and provided an input to a computer program, PDFIt. The program was developed to apply the uniform, normal, lognormal, exponential, Weibull, gamma, and beta probability distributions to the input data. The parameters of these distributions were calculated using the method of MLEs. MLEs, in general, provide the most satisfactory estimates of parameters. The User selects the best fitting distribution using a combination of visual assessment and goodness-of-fit test results.

The aim of the experimental analysis was to identify a theoretical probability distribution that is representative of the concrete placement process. The results can be summarized as follows:

1. Through visual assessment, it was determined that the lognormal distribution generally provides the optimum representation of the process. When individual concrete pours were judged visually, the lognormal distribution was the predominant representation in a significant number of cases. The conclusion that the lognormal distribution represents the concrete placement process acquires further support from the results of the visual appraisal of large sets of concrete pours.

2. The Weibull and gamma distributions provide close, although underestimated, representations of the large input data sets used in Experiment One. The importance of achieving an accurate representation of the input data when simulating a process cannot be overemphasized. Therefore, any over- or underestimation will reduce the accuracy of the analysis.

3. The goodness-of-fit tests provided some support to the results of the visual assessments. In some instances, the K-S test, highly ranked the distributions which were judged (through visual assessment) not to closely represent the observed data. It can be concluded that while the K-S test does not provide wholly inaccurate results, the fact that it does not place any emphasis on the tail of a probability distribution is...
likely to be significant with the construction distributions under investigation. The underlying histogram for concrete placing data has, in general, a tail (right or left) which is a prominent feature. Therefore, a test which emphasizes tail weighting was more appropriate to assess the goodness of fit. Such a test is the A-D. For individual pours the A-D test ranked highly the lognormal distribution, and this corresponds with the results of the visual assessment.

This paper has presented the lognormal distribution as a sufficiently flexible theoretical probability distribution to represent the concrete placing process. The selected distribution can be used to create random variates for use in a simulation model of the process. The generation of lognormal random variates can be attained efficiently through the use of an acceptance-rejection method as described in Law and Kelton (1991). The model, upon validation, can be used to yield estimating and planning information, which could improve the performance of civil engineering construction companies in actual concrete placement operations.

Notation

The following symbols are used in this paper:

- \( A_n \): Anderson-Darling test statistic;
- \( D_n \): Kolmogorov-Smirnov test statistic;
- \( F(x) \): fitted distribution function;
- \( f(x) \): empirical distribution function from the data set, \( X_1, X_2, \ldots, X_n \);
- \( f(x) \): hypothesized density functions, assuming one unknown parameter, \( \theta \);
- \( L \): lower limit of distribution;
- \( U \): upper limit of distribution;
- \( sup \): set of random numbers \( A \) is the smallest value that is greater than or equal to all members of \( A \); and
- \( \Psi(x) \): weight function = \( 1/[F(x)(1-F(x))] \).

References


Planning, estimation and productivity in the lean concrete pour

Paul Dunlop and Simon D. Smith

Introduction

Latham (1994) suggested that productivity improvements in the UK of up to 30 per cent were necessary to face the challenges of the next millennium. Egan (1998) added to this and suggested that productivity be increased by 10 per cent per year. At the time of this report, productivity increased by some 5 per cent per year with the best projects demonstrating increases of up to 15 per cent (Egan, 1998). These figures reflect the current improvements in the UK construction industry at present, although clearly there is still room for further improvements. The potential of new and existing production theories can and should be tapped.

One such technique, which has been developed from the manufacturing industry, is lean construction. Lean construction has the goal of meeting the customer needs better while using less of everything. It rigorously takes advantage of production management principles and is dedicated to eliminate wasteful activities within the construction industry.

The construction industry is one with a large number of specialised areas and disciplines, many based on cyclic processes. One such process is concreting, which can be considered to include several tasks within the process, namely: batching, transportation, placement and return to the batching plant. In this paper, it is intended to show that by using lean construction techniques and principles, first it is possible to identify the wasteful activities and second, to make concessions for them, leading to a better understanding of such processes and improving the overall performance. This is done via a comparison of four measures of concrete productivity.

(1) Actual productivities measured during a study of 202 concrete pours.
(2) Potential productivities on these pours if lean principles were used.
(3) Productivities estimated using construction planners’ manuals.
(4) Productivities estimated using a linear regression model of the observed pours.

Lean construction principles

Lean construction has been developed from management principles used by Toyota, who...
doggedly set about eliminating waste in the car manufacturing industry. The term “lean” was coined by the research team working on international auto production to reflect both the waste reduction nature of the Toyota production system and to contrast it with craft and mass forms of production (Womack et al., 1991). Whilst lean production was successful in the car manufacturing industry, many believed that it would not be applicable in the dynamic world of construction. Subsequently, a great deal of work has been carried out in this area with many favourable findings.

Lean construction advocates the elimination of waste whilst using fewer inputs. Howell (1999) states that moving towards zero waste – perfection – shifts the improvement from the activity to the delivery system. While much work has been carried out concerning particular activities, the delivery system is regularly being overlooked. Lean principles, such as just-in-time (JIT) delivery has gone some way in addressing this issue. Tommelein and Li (1997) have been active in this area and have explained concepts underlying a JIT production system. A further “lean” principle is the analysis of all operations as a series of flow and conversion activities (Koskela, 1992). Conversion activities are those operations performed in adding value to the material or information being transformed to a product. Flow processes represent activities such as inspection, moving and waiting and are indicated in the shaded boxes. This method of analysis, adopted by Koskela (1992, 2000) is appropriate for concrete operations. It allows us to break down the process and easily identify all tasks that cause delays, and material misuse, and thus waste. Quite often models are developed that only deal with conversion processes – these are the activities that add value to the final product and it is reasonable to attempt to maximise them. Alternatively we may also consider the flow processes which, whilst not always adding value, are an integral part of the overall operation. A revised modelling methodology would therefore attempt to maximise the output from conversion activities whilst also minimising the effects of flow processes (i.e. minimising waste). Methodologies such as JIT and total quality management (TQM) can greatly reduce the amount of waste involved in these flow processes: JIT will control the amount of moving and waiting involved in the operation and TQM will ensure that inspections are carried out effectively to a high standard, thus reducing the amount of rework.

**Applying lean construction principles to concrete operations**

Concrete operations are littered with variables and uncertainties. Unless these are considered at the early planning stages, many can result in wasteful activities, which are difficult to manage once construction has started. It may be possible to apply lean construction principles to identify and manage these uncertainties.

First, consider the process at the concrete batching plant and construction site as a series of flow and conversions (Figure 1). Conversion activities are those operations performed in adding value to the material or information being transformed to a product and are shown unshaded. Flow processes represent activities such as inspection, moving and waiting and are indicated in the shaded boxes. This method of analysis, adopted by Koskela (1992, 2000) is appropriate for concrete operations. It allows us to break down the process and easily identify all tasks that cause delays, and material misuse, and thus waste. Quite often models are developed that only deal with conversion processes – these are the activities that add value to the final product and it is reasonable to attempt to maximise them. Alternatively we may also consider the flow processes which, whilst not always adding value, are an integral part of the overall operation. A revised modelling methodology would therefore attempt to maximise the output from conversion activities whilst also minimising the effects of flow processes (i.e. minimising waste). Methodologies such as JIT and total quality management (TQM) can greatly reduce the amount of waste involved in these flow processes: JIT will control the amount of moving and waiting involved in the operation and TQM will ensure that inspections are carried out effectively to a high standard, thus reducing the amount of rework.

**Lean principles used to reduce waste in flow processes**

With the advent of lean thinking in construction, many heuristic principles have evolved. Many of these are applicable to concrete operations and may well reduce and control the amount of waste that is present in flow processes. Consider the following principles with respect to concrete operations:

- **Predict and reduce variability:** and
- **Reduce the cycle time.**

**Predict and reduce variability**

This is one of the most critical steps that can be made to reduce waste and increase the performance levels of concrete operations. The dynamic nature of concrete operations has led to research identifying a very large amount of variability (Anson and Wang, 1998; Dunlop and Smith, 2000). The authors used data collected on civil engineering projects and, after identifying a number of measurable variables, carried out a regression analysis to reveal the most significant. A summary of the findings of this study is presented later in this paper.
If variability can be predicted then variability can be managed. For example, it is clearly useful to have a prediction of total pour time. This enables the activity, and those surrounding it, to be planned adequately and make sure that an adequate amount of resources and materials are on hand.

Reduce the cycle time
If the conversion variables (for example, truck-mixer discharge time) are predicted and reduced then cycle time shall automatically be improved. More significantly, perhaps, the cycle time can be improved even further by reducing waiting times, delays, moving times and inspection times, i.e. the flow processes.

Flow processes are easily thought of and measured in terms of time. Time is a more useful and universal metric than cost and quality because it can be used to drive improvements in both (Krupka, 1992). When measuring cycle time in concrete operations it includes the following: pumping time, inspection time, queuing time, wash-out time and transportation time from batching plant to site and back again. From all of these, the only time that is strictly non-value adding is the queuing time. By using JIT objectives it is possible to eliminate this, and hence reduce the cycle time. In an ideal world it would be possible to plan operations such that one truck-mixer finishes discharging its concrete just as the next is arriving on site. This also assumes that the placing team can work continuously.

Productivity rates in concreting operations
Just as flow processes are easily thought of in terms of time, construction operations are easily thought of in terms of productivity rates. Productivity rates rank amongst the most essential data needed in the study of construction productivity (Herbsman and Ellis, 1990).

In concreting operations, we can assume that due to the relatively fixed size of the placing team, an adequate measurement of the overall productivity can be the amount of concrete placed in an operation per hour. Even this productivity measurement can represent many different values. The duration of the concrete pour can represent different times depending on what start time is taken. It can be taken as the time at which the first load of concrete is batched or the time at which the first concrete is discharged into the formwork. Each will give a slightly different value of productivity and both can be perceived to be relevant: the contractor is only interested in the time taken to place the concrete, while the supplier will be interested in the truck productivity including travel times. For the purpose of this study, the duration of the
operations will be from the time the first load is batched to the time at which the last concrete is placed.

In all cases, it is important to appreciate the maximum productivity achievable of the plant being used, i.e. the concrete pump and the truck-mixers. Care must be taken in assuming productivity values for any concrete pour using historical company data or calculated from manufacturer's handbooks, due to the uniqueness of individual pours and, in particular, the fact that productivity is highly dependent on matching the correct number of truck-mixers to the concrete pump.

A productivity analysis of concrete operations in the UK

If productivity rates on-site are to be maximised then it is important that the delivery of concrete is regular and adheres to the contractor's demands. Productivity rates are also dependent on the type of placing equipment used and whilst it is acknowledged that there are several methods of placement, results shall only consider placement via a mobile concrete pump. In this section, different methods of predicting these productivity rates are shown and compared to those observed on-site.

Data and information collected on-site

The time-based studies were carried out in the UK in 2000 and involved the observation of over 200 concrete pours on three separate civil engineering projects. Each project involved the construction of wastewater treatment plants and were carried out simultaneously. All three construction projects were located within a 50-mile radius by the same contractor. All concrete was placed using a mobile pump and each batching plant was within 6 miles of the construction project. The typical crew size, including concreting gang, pump operator and concrete tester, was eight.

Table I summarises the data collected on these three projects; each pour observed has been divided into wall, column and base pours as they are very different from each other in terms of resources and planning as discussed later. The mean pour size in the sample was 68.9 m$^3$, reflecting the amount of wall and column pours observed (67 per cent of all pours). One-quarter of the sample consisted of pours smaller than 32 m$^3$ and one-quarter were greater than 66 m$^3$. The results found in this paper therefore represent the smaller end of concrete pours, which present their own planning and scheduling problems due to their abundance and fragmented nature.

The mean duration of all pours was found to be 272.4 min (approximately 4.5 h), with one-quarter of the pours being less than 180 min (3 h) and one-quarter greater than 340 min (5 h 40 min). The type of pours observed on-site can explain these durations. Wall and column pours have to be poured in a controlled manner and while they may not be a large pour in terms of volume, they can often take a substantial amount of time. In this study, the mean duration for wall and column pours combined was found to be 242 min (4 h 2 min) for a total mean volume of 46 m$^3$ compared to 334 min (5 h 34 min) for a total mean volume of 116 m$^3$ for all base pours. Figure 2 shows the scatter found in the rate of pour for the 202 observations. The lower end of the plot reflects the large amount of wall and column pours observed. If we use an example of 200 m$^3$ pour from the regression model we would expect a duration of 519 min.

As well as the data shown in Table I, it was also important to record individual events during the course of each pour. By observing the batch, arrival on-site, start and finish discharging times, it was possible to calculate many other parameters (Table II) such as: pump times, truck interarrival times (time between trucks arriving on-site), queuing times of trucks on-site and the time taken for trucks to position. Also the truck and pump and placing team idle times could also be calculated.

Table II shows the time characteristics for all concrete pours observed. Significantly, we can see from columns four, five and six, that on an average the amount of time spent on queuing and positioning on-site (non-value adding or waste) is actually greater than the time taken to discharge the concrete into the pump (value adding). Columns seven and eight indicate total idle time on-site for both types of plant per pour. It has also been able to calculate the cost per cubic metre of this waste using cost data provided by a contractor's estimating department.

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Planning, estimation and productivity in the lean concrete pour

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Numbers and types of pour, sizes and durations for all pours observed

<table>
<thead>
<tr>
<th>Type of pour</th>
<th>Number of pours</th>
<th>Mean pour size (m³)</th>
<th>Mean pour duration (min)</th>
<th>Mean truck-mixer volume (m³)</th>
<th>Mean number of trucks on pour</th>
<th>Mean cycle time (min)</th>
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<td>Wall</td>
<td>1</td>
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</tr>
<tr>
<td>Base</td>
<td>5</td>
<td>251.4</td>
<td>639.2</td>
<td>7.5</td>
<td>6.4</td>
<td>91.6</td>
</tr>
<tr>
<td>Overall</td>
<td>10</td>
<td>143.9</td>
<td>420.9</td>
<td>7.2</td>
<td>4.5</td>
<td>76.0</td>
</tr>
<tr>
<td>Wall</td>
<td>9</td>
<td>52.0</td>
<td>253.0</td>
<td>7.2</td>
<td>4.2</td>
<td>121.9</td>
</tr>
<tr>
<td>Column</td>
<td>2</td>
<td>66.5</td>
<td>329.5</td>
<td>6.8</td>
<td>5.5</td>
<td>130.0</td>
</tr>
<tr>
<td>Base</td>
<td>9</td>
<td>241.5</td>
<td>538.9</td>
<td>7.2</td>
<td>7.8</td>
<td>96.8</td>
</tr>
<tr>
<td>Overall</td>
<td>20</td>
<td>138.7</td>
<td>389.3</td>
<td>7.2</td>
<td>6.0</td>
<td>111.4</td>
</tr>
<tr>
<td>Wall</td>
<td>104</td>
<td>46.7</td>
<td>250.4</td>
<td>7.4</td>
<td>2.8</td>
<td>81.1</td>
</tr>
<tr>
<td>Column</td>
<td>15</td>
<td>34.4</td>
<td>178.1</td>
<td>7.1</td>
<td>2.7</td>
<td>54.0</td>
</tr>
<tr>
<td>Base</td>
<td>53</td>
<td>81.8</td>
<td>270.3</td>
<td>7.6</td>
<td>3.5</td>
<td>69.1</td>
</tr>
<tr>
<td>Overall</td>
<td>172</td>
<td>56.4</td>
<td>250.2</td>
<td>7.4</td>
<td>3.0</td>
<td>75.0</td>
</tr>
</tbody>
</table>

Actual productivity

For the sample of pours, it was possible to calculate the actual productivity achieved (m³/h) as well as the productivity rates which could have been achieved if lean principles had been applied (Table III). Actual productivity was determined by dividing total volume by pour duration (time from moment of first batch to last batch poured).

Considering the overall actual productivity for the sample, it is possible to differentiate between the three types of structures encountered. It can be seen that wall and column pours are related in many ways: the

Figure 2 Relationship between pour duration and volume (for all pours observed)

![Graph showing relationship between pour duration and volume](image)

\[
y = 1.8853x + 142.49
\]

\[
R^2 = 0.7852
\]
volume of concrete being placed is similar and the productivity rates achieved are similar (≈ 11 m$^3$/h) and reflect the way in which they are poured. Wall and column structures have to be placed in a controlled manner due to their shape so that no structural damage or weakness occurs.

For base pours, the mean volume of concrete being placed was 116 m$^3$ and a higher

<table>
<thead>
<tr>
<th>Type of pour</th>
<th>Number of pours</th>
<th>Mean pour size (m$^3$)</th>
<th>Mean measured actual productivities Overall (m$^3$/h)</th>
<th>Productivities using lean principles Overall (m$^3$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>1</td>
<td>23.5</td>
<td>15.4</td>
<td>17.8</td>
</tr>
<tr>
<td>Column</td>
<td>4</td>
<td>88.0</td>
<td>8.4</td>
<td>14.9</td>
</tr>
<tr>
<td>Base</td>
<td>5</td>
<td>251.4</td>
<td>24.0</td>
<td>26.7</td>
</tr>
<tr>
<td>Overall</td>
<td>10</td>
<td>143.9</td>
<td>16.9</td>
<td>21.1</td>
</tr>
<tr>
<td>Wall</td>
<td>9</td>
<td>52.0</td>
<td>12.4</td>
<td>16.1</td>
</tr>
<tr>
<td>Column</td>
<td>2</td>
<td>66.5</td>
<td>11.2</td>
<td>11.8</td>
</tr>
<tr>
<td>Base</td>
<td>9</td>
<td>241.5</td>
<td>26.0</td>
<td>30.1</td>
</tr>
<tr>
<td>Overall</td>
<td>20</td>
<td>138.7</td>
<td>18.4</td>
<td>22.0</td>
</tr>
<tr>
<td>Wall</td>
<td>104</td>
<td>46.7</td>
<td>11.2</td>
<td>14.3</td>
</tr>
<tr>
<td>Column</td>
<td>15</td>
<td>34.4</td>
<td>11.0</td>
<td>13.1</td>
</tr>
<tr>
<td>Base</td>
<td>53</td>
<td>81.8</td>
<td>16.7</td>
<td>20.8</td>
</tr>
<tr>
<td>Overall</td>
<td>172</td>
<td>56.4</td>
<td>12.9</td>
<td>16.2</td>
</tr>
<tr>
<td>All Wall</td>
<td>114</td>
<td>47.5</td>
<td>11.3</td>
<td>14.4</td>
</tr>
<tr>
<td>All Column</td>
<td>21</td>
<td>35.4</td>
<td>10.2</td>
<td>13.3</td>
</tr>
<tr>
<td>All Base</td>
<td>67</td>
<td>116.0</td>
<td>18.5</td>
<td>22.5</td>
</tr>
<tr>
<td>All pours</td>
<td>202</td>
<td>68.9</td>
<td>13.6</td>
<td>17.0</td>
</tr>
</tbody>
</table>
productivity rate of 18.5 m³/h was achieved. The nature of base pours results in concrete being placed as fast as possible and therefore, the overall productivity of such an operation will have an upper limit of the capacity of the concrete pump.

For the sample containing 202 pours and an average pour size of 69 m³, a mean productivity rate of 13.6 m³/h was found. Some comparative figures for pumping in the UK, West Germany and Hong Kong are available (Anson and Wang, 1998; Anson et al., 1989). The UK-based study had a mean pour size of 92 m³ and a placing speed of 15.5 m³/h; the West German study had a mean pour size of 170 m³ and a placing speed of 20.5 m³/h and the Hong Kong-based study had a mean pour size of 144 m³ and a placing speed of 21.4 m³/h. The UK sample numbered 70, the West German sample numbered 32 and the Hong Kong-based sample numbered 51 pours.

Achievable productivity rates using lean principles
Lean construction principles, although not knowingly in use for the sampled pours, could potentially make a significant difference in productivity rates. Column six in Table III shows the productivity rates that could have been achieved if the lean ideas, discussed earlier, had been used in the sampled pours. A “lean” concrete pour will be one in which the waste has been identified and eliminated. Essentially, the rates in column six show the productivity that would be achieved if all truck and pump idleness (waste) were eliminated. Idle times can be measured relatively easily on-site and have been summarised in Table H. On average and overall, the productivity could have been increased by 3.4 m³/h (25 per cent); for a project with 15,000 m³ of concrete, this is a time saving of more than 200h.

Methods available to estimate productivity
We may compare the actual and potential outputs from the observed operations with estimated productivities. Planners and estimators encountered during the course of this study were in agreement that productivity rates should be handled with great care. For them, it was more important to consider variables such as location, weather, required method of placement and the skill of labour available.

Construction planner’s manuals
An estimation of productivity was calculated using a major UK contractor’s planning figures. Due to the sensitivity of such material, the contractor cannot be identified. For pumped pours, based on a mobile pump whose capacity is 20-30 m³/h, the following placing speeds are used in the planning of concrete operations, considering the planner’s individual allowance for variations within the operation:

- base pours – 13.3 m³/h;
- wall pours – 9.6 m³/h;
- column pours – 8.7 m³/h.

These estimations of productivity reflect those found in Table III and provide a useful first pass for a project bill of quantities to establish labour requirements. They could also be used as a guide subjected to specific planning of a project.

A regression analysis for predicting productivity
Another useful technique for estimating outputs in concrete operations is regression analysis. Regression analysis has been used to effect in many other construction processes, for example, earthmoving operations (Smith, 1999). It allows planners to estimate outputs considering all those variables that are measurable based on past concrete pours. The regression analysis carried out for this study was based on the data collected during the pours observed for the main study in this paper. A number of explanatory variables were identified and recorded. These include time of year, average volume of truck-mixer, total volume of concrete, number of loads, number of truck-mixers on project, average truck-mixer cycle time, type of structure, start time, project at which pour occurred and the concrete mix used. All of these explanatory variables were subjected to a backward stepwise regression analysis to find their significance to the output, which in this case was actual productivity. Using this method, a regression equation is fitted to the above variables, and a decision is made as to whether all the explanatory variables are significant. If the variable is significant it remains in the model; otherwise it is removed and the regression analysis repeated. The statistical t-test shall be used to determine initially the significance of each explanatory variable, with each computed coefficient subjectively checked for a rational cause and
Planning, estimation and productivity in the lean concrete pour

Paul Dunlop and Simon D. Smith

The t-statistic is the ratio of the coefficient to its standard error; a large t-ratio is therefore desirable. The critical t-ratio, at a significance of 5 per cent, is $t \approx 1.98$, where $n$ is the number of observations in the sample (202), and $p$ is the number of explanatory variables (ten). This implies that all variables with an absolute t-ratio of $<1.98$ are not significant to the regression model.

The backward stepwise regression analysis was required to be carried out for four runs; the regression and ANOVA statistics can be seen in Tables IV and V. Table V also indicates the coefficient of determination, $R^2$, showing that 80 per cent of the variation in the explanatory variables is explained by the regression model.

The variable with the highest t-ratio in Table IV was found to be the type of pour. This confirms the different methods that have to be followed when dealing with different pour types. One variable that was perhaps surprisingly removed from the regression model is the truck cycle time, which was found to be insignificant after the first run. This means that the cycle time does not influence productivity - clearly, in some instances, this cannot be true - but what are such instances? Considering Table II, it can be seen that in this particular sample, the truck wait time on-site is nearly 7 min on average, therefore operations are, on an average, over-resourced and over-wasteful. In such situations, an increase in cycle time can occur without affecting productivity (the increase in cycle time would result in the truck arriving on-site later which in turn would reduce the on-site truck wait time), thus making the truck cycle time non-significant. If, conversely, operations were under-resourced then as the cycle time increases, pump idleness increases and hence productivity will decrease.

The derived model for actual productivity using a single mobile pump can therefore be given by (notation given in Table IV):

$$P_{act} = 1.4191N_{tp} + 0.1188V_{c} + 0.4812N_{i} + 0.86V_{i} + 0.4355T_{st} - 0.4565N_{1} - 4.6521$$

Summary of concrete productivity rates

Four different measures of productivity rates of the concrete operations are shown within this study. They are the actual productivity recorded, potential productivity rates estimated considering lean principles, productivity rates estimated using information from a major UK contractor's planning department, and productivity rates calculated using a simple regression analysis. Table VI shows a summary

### Table IV Regression on actual productivity – final run

<table>
<thead>
<tr>
<th>Explanatory variable (1)</th>
<th>Notation</th>
<th>Coefficients (2)</th>
<th>t-ratio (3)</th>
<th>Lower 95 per cent (4)</th>
<th>Upper 95 per cent (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of pour N&lt;sub&gt;tp&lt;/sub&gt;</td>
<td></td>
<td>1.42</td>
<td>6.33</td>
<td>0.98</td>
<td>1.86</td>
</tr>
<tr>
<td>Total volume V&lt;sub&gt;c&lt;/sub&gt;</td>
<td></td>
<td>0.12</td>
<td>4.27</td>
<td>0.06</td>
<td>0.17</td>
</tr>
<tr>
<td>Number of trucks on job N&lt;sub&gt;i&lt;/sub&gt;</td>
<td></td>
<td>0.48</td>
<td>2.66</td>
<td>0.12</td>
<td>0.84</td>
</tr>
<tr>
<td>Average volume of load V&lt;sub&gt;i&lt;/sub&gt;</td>
<td></td>
<td>0.86</td>
<td>2.64</td>
<td>0.22</td>
<td>1.50</td>
</tr>
<tr>
<td>Start time T&lt;sub&gt;st&lt;/sub&gt;</td>
<td></td>
<td>0.44</td>
<td>2.27</td>
<td>0.06</td>
<td>0.81</td>
</tr>
<tr>
<td>Number of loads N&lt;sub&gt;i&lt;/sub&gt;</td>
<td></td>
<td>-0.46</td>
<td>-2.21</td>
<td>-0.86</td>
<td>-0.05</td>
</tr>
<tr>
<td>Job N&lt;sub&gt;j&lt;/sub&gt;</td>
<td></td>
<td>0.88</td>
<td>2.18</td>
<td>0.08</td>
<td>1.69</td>
</tr>
<tr>
<td>Intercept</td>
<td></td>
<td>-4.65</td>
<td>-1.75</td>
<td>-9.88</td>
<td>0.58</td>
</tr>
</tbody>
</table>

### Table V ANOVA statistics for regression on actual productivity – final run

<table>
<thead>
<tr>
<th>ANOVA statistics</th>
<th>Degrees of freedom (1)</th>
<th>Sum of squares (3)</th>
<th>Mean square (4)</th>
<th>F (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>7</td>
<td>4721.1</td>
<td>674.4</td>
<td>110.3</td>
</tr>
<tr>
<td>Residual</td>
<td>194</td>
<td>1185.8</td>
<td>6.1</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>201</td>
<td>5907.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$R^2$</td>
<td>79.2 per cent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table VI Summary of all calculated productivity rates

<table>
<thead>
<tr>
<th>Type of pour</th>
<th>Actual productivity rates (m$^3$/h)</th>
<th>Productivity rates considering lean using information from a professional planner (m$^3$/h)</th>
<th>Productivity rates from regression analysis (m$^3$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>11.3</td>
<td>14.4</td>
<td>9.6</td>
</tr>
<tr>
<td>Column</td>
<td>10.2</td>
<td>13.3</td>
<td>8.7</td>
</tr>
<tr>
<td>Base</td>
<td>18.5</td>
<td>22.5</td>
<td>13.3</td>
</tr>
<tr>
<td>Overall</td>
<td>13.6</td>
<td>17.0</td>
<td>–</td>
</tr>
</tbody>
</table>

of the productivity rates using the four different methods. Table VI highlights some interesting findings about the approaches to productivity estimation within the construction industry. Planners appear to be content in underestimating concrete placing productivity, possibly to enable planning for unforeseen happenings within the operations. When lean construction principles are considered, it is evident that it is possible to drive up productivity levels with great effect.

The actual productivity measured for the pours observed on construction projects in the UK seem to support planners’ predictions that base pours are placed at a higher speed than column or wall pours. The regression model for actual productivity that has been undertaken in this paper has provided an equation that describes 80 per cent of the variance in a large set of data obtained from real concrete operations. The productivity rates found from the regression model closely mirror the actual productivity recorded, as would be expected since the regression model is based on these data. Further, it should be noted that the regression model is derived from the data that are not lean and therefore do not, and cannot be expected to, predict productivities when lean principles are implemented.

Conclusions

This paper has presented factual productivity rates for concrete placing within the UK construction industry. It allows the industry to see what improvements are to be made if Latham’s (1994) dream of an increase of 30 per cent in productivity rates is to be achieved. Egan (1998) sets a new set of targets for the UK construction industry, he suggested that productivity be increased by 10 per cent per year. At the time of his report, productivity was increased by an average of 5 per cent per year with the best projects demonstrating increases of up to 15 per cent. Although many methods were reviewed to aid the industry achieve these increases, lean construction must be seen as a philosophy that is practical and has had a vast amount of research carried out into it to make it work.

A “lean” concrete pour will be one in which the waste has been identified and eliminated. In order to achieve a lean pour, it is necessary to have a good knowledge of as many variables within the concreting cycle as possible. In this study, it has been shown that by eliminating both truck and pump idle times there is the potential to achieve a concrete pour that has less waste and a higher productivity. It has been demonstrated (Table VI) that there is a potential increase in productivity of 25 per cent. To achieve such a situation would undoubtedly be difficult – but it is clear that an analysis of “waste” activities is not routinely carried out on UK concreting operations. If such a situation were to change, and the anticipated waste of a concreting activity were estimated, then moves could be made to reduce it. For example, if planners estimated that a resource level resulted in high pump idleness, it could be requested that an extra truck-mixer was used.

Planning operations require adequate tools for the prediction of productivity. It has been shown that a useful tool may be a regression model. The regression analysis in this paper has shown that by identifying and measuring a number of explanatory variables within concrete operations they can be used to model the overall operation. The regression analysis carried out in this paper showed the most significant variables

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to be type of pour, total volume of concrete, number of trucks on project, average volume of load, pour start time, number of loads on project and finally project on which the pour has taken place. The regression model for actual productivity, using the seven most significant variables, has provided an equation that describes 80 per cent of the variance in the large set of data obtained from real concrete operations.

The tools and techniques presented in this paper have shown that with, effective and efficient, planning and scheduling of concrete operations, it is possible, in at least this specific area, to increase productivity rates. Only by every individual area of work doing likewise will Latham’s and Egan’s aspirations for the construction industry be shown to be reality.

References


Further reading


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ESTIMATING KEY CHARACTERISTICS OF THE CONCRETE DELIVERY AND PLACEMENT PROCESS USING LINEAR REGRESSION ANALYSIS

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Concrete operations include various processes such as batching, transport and placement all of which are subject to unplanned disruptions and irregularities. The problem of accurately estimating the productivity of concrete operations is not a new one and unless a definitive model is developed it is unlikely that the efficiency and effectiveness of these operations is improved. The problem is exacerbated by the poor understanding of some of the key characteristics involved in concrete operations, which is one of the most common operations in today's construction industry.

This paper presents a multiple linear regression analysis based on data collected on a major civil engineering project in the North-East of Scotland involving three smaller projects. From the three sites, a total of 202 separate concrete operations were observed for the entirety of the process, thus supplying a generous set of data recording multiple cycles. The results show a strong linear relationship between the chosen operating conditions and productivity. The derived model is then validated using data collected on a different site with some interesting and favourable findings.

Keywords: Concrete operations; Productivity; Regression analysis

INTRODUCTION

Concrete operations can be described as including several processes such as batching, transport and placement, and are common to many construction sites throughout the world. It has been recognised that there are a variety of methods that are being used in order to maximise the output and ultimately the expected profits on them (Smith, 1998; 1999a).

The required quality of finished concrete is usually very well defined in the project specifications, however, concrete production procedures are often unspecified, and contractors are required to select their own procedures. The resulting concrete quality often suffers from a lack of standard production procedures. This ultimately increases the risk of reworking unsatisfactorily produced concrete operations, impairs productivity and increases costs. It is anticipated that with accurate planning and estimation a more rigid technique can be
developed that will aid the construction industry as a whole to obtain maximum productivity from concrete operations.

In concrete operations unanticipated conditions and actions can result in a loss of productivity; for example, adverse weather, lack of management control and plant breakdown. The major problem is that the natural variability of all the factors within the system will influence the output from concreting operations. Table I lists some of the factors that the author considers to influence the output in concreting operations with a note as to how determinable they may be to the planning engineer in the early stages of a project's life. The table reflects conditions and practises encountered by the author on UK constructions sites.

This paper will look at the concreting system that, in its simplest form, consists of batching, transport and finally placement. Data obtained from several construction sites in the UK, specialising in major civil engineering works shall be studied. Particular attention will be given to the productivity (and loss of productivity) of these concreting operations, as well as the factors influencing the operations, such as delays and idleness. The study will be carried out using regression techniques and it is anticipated that a model will be developed that will allow planners and estimators to predict productivity rates.

### TABLE I Factors Influencing Concrete Operations.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Determinability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between batching plant and site</td>
<td>High</td>
</tr>
<tr>
<td>Road conditions between batching plant and site</td>
<td>Medium</td>
</tr>
<tr>
<td>Traffic levels on road between batching plant and site</td>
<td>Medium</td>
</tr>
<tr>
<td>Site characteristics</td>
<td>Medium</td>
</tr>
<tr>
<td>Access routes on site</td>
<td>Medium</td>
</tr>
<tr>
<td>Weather</td>
<td>Very low</td>
</tr>
<tr>
<td>Truck-mixer travel speeds</td>
<td>Medium</td>
</tr>
<tr>
<td>Truck-mixer capacity</td>
<td>High</td>
</tr>
<tr>
<td>Truck-mixers available for use</td>
<td>Medium</td>
</tr>
<tr>
<td>Truck-mixer cycle times</td>
<td>Medium</td>
</tr>
<tr>
<td>Pump operator ability</td>
<td>Low</td>
</tr>
<tr>
<td>Pump capacity</td>
<td>High</td>
</tr>
<tr>
<td>Age of pump</td>
<td>High</td>
</tr>
<tr>
<td>Type of pump (mobile or static)</td>
<td>High</td>
</tr>
</tbody>
</table>

THE CONCRETING PLACING PROCESS EXPLAINED

At this stage it is useful to look at the concrete placing cycle in a schematic diagram (Fig. 1). The system can be treated as a single server queuing system and for this paper the method of concrete placement will be via a pump. No account has yet been made of the batching process, which can be considered a system in its own right.

In 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. 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 occurs. 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 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.

**KEY CHARACTERISTICS OF CONCRETE OPERATIONS**

**Concrete Productivity Rates**

Productivity rates rank amongst the most essential data needed in the study of construction productivity (Herbsman and Ellis, 1990). These productivity rates are very useful to many people within the industry but none more so than planning engineers. These rates can enable planners to estimate and schedule future pours and are also useful for resource levels, accounting and cost control. Many planning engineers often maintain a large databank of basic productivity rates and will adjust these for each individual project, taking into account specific site factors and conditions which may influence productivity rates.

Much has been said about the factors that will ultimately affect productivity within the construction industry. Interestingly, Christian and Hachney (1995), in their study of productivity rates, found that there existed ‘substantial agreement’ between the average productivity rates actually measured on site and of those used by the planning engineers. In the author’s experience this has not been the case in concreting operations in the UK. Christian and Hachney do go on, however, to point out that when significant differences do occur in actual productivity they are caused mainly by waiting and idle times and it is the modelling of these ‘waste activities’ that is, perhaps, difficult to achieve.

Productivity can be defined in many ways. In construction, productivity is usually taken to mean operation or process productivity, that is units of work placed or produced per ‘man’-hour. This measure of productivity has several advantages:

1. the meaning of the term process productivity is relatively well understood;
2. process productivity is often the greatest source of variation in overall construction productivity; and
3. the productivity of other inputs can often be measured with respect to process productivity.
In concreting operations we can assume that concrete placed per man-hour, for an entire operation, is an adequate means of measuring productivity. However, in a planning situation it may be more suitable to consider productivity in terms of operative hours per unit of work, e.g. 20 hours/10 m$^3$ = 2 operative hours per m$^3$.

In concrete operations the productivity rate has to take into account the potential productivity of, say, the concrete pump, which is distributing the required concrete into the formwork, and the delivery vehicles, which are transporting the concrete. However, it is difficult to estimate actual productivity values for any concrete pour using historical company data or calculated from manufacturer's handbooks, due to the uniqueness of individual pours. If these methods are followed without prior consideration it may lead to levels of productivity that are rarely possible to achieve in actual operations with consequent negative effects on a working programme.

Concreting productivity is governed by the prime mover, which for the purpose of this paper shall be a concrete pump (this term could also be applied to other methods of placement such as, crane and skip). The maximum potential productivity of a system is dependent on the output from the prime mover – this maximum can only be increased by changing the characteristics of this prime mover or by increasing the number of prime movers on a particular job. In reality this level of maximum productivity is rarely reached, at least not in an efficient manner – it being reduced by random variables within the system that will result in waiting and idle times.

Concrete Pump Idleness

Pump idleness in concrete operations is unfortunately a common occurrence and is often a result of either poor and inadequate management or the influence of factors that are difficult to plan and schedule. The concrete pump will become inactive in the majority of operations due to the necessity of the delivery trucks to manoeuvre and position their chutes at the hopper of the pump. This is, in most cases, a tolerable and necessary delay to the overall operation, however as will be seen pump idle times will greatly exceed this tolerated time. Pump idle times will be increased by:

- Rejection of concrete that does not fall within given specifications
- Plant breakdown
- Problems arising from difficulties in placing the concrete
- Late delivery of concrete (including under-provision of trucks)
- Lack of skilled labour
- Poor site conditions and access roads to site

When the concrete pump becomes idle the cost to the contractor can be very significant: the pump, the pump operator, the placing teams and any other ancillary resources must be considered.

Delivery Truck Idle Time

In concrete operations it is very easy to over-provide the amount of truckmixers for concrete delivery. This can be regarded to be unfavourable to the concrete supplier as it limits the amount of trucks that is available for other jobs. The contractor may benefit from this situation, although it could be implied that the supply rate of concrete is too fast for the contractor to take advantage of. This highlights the need for good communication to exist between the contractor and the supplier, so that both are able to benefit from an optimal delivery regime.
Another adverse effect of having trucks queuing on site is highlighted by Anson and Wang (1998). They state that placing teams are not immune to the pressure caused by a queue of truckmixers waiting to be unloaded. This may cause an indirect loss of productivity due to the negative psychological effects.

OBSERVED CONCRETE OPERATIONS

For the purpose of this paper a wastewater project was observed in the North-East of Scotland (Project A). The project involved three separate wastewater treatment plants within an 80-mile area. Each plant was constructed under a Private Finance Initiative contract by the same collaboration of contractors. All three plants, or 'sub-projects' had their own separate characteristics and uniqueness and had large volumes of concrete in their design. The data was gathered on site directly over a four-month period.

From these three sub-projects a total of 202 separate concrete operations were observed in their entirety, thus supplying a generous set of data recording multiple cycles. Concreting operations were typical and conformed to those discussed above and indicated in Figure 1; each operation would also have varying combinations of plant capacity and quantity, concrete types, operating conditions, weather, time of year, etc. This data set of operations, due to its large size and varied conditions, therefore, represent a remarkable sample of concreting activities.

Over the observation periods, the event times for each truck-mixer were recorded as well as the quantities of plant, volume of concrete per delivery truck and concrete slump (this was tested before concrete was allowed to be discharged into formwork in accordance with BS specifications). From these data it was possible to calculate a further 14 characteristics. Table II summarizes the events and characteristics that were observed and calculated for the 202 operations. These observed and calculated characteristics form the basis for the model development. It should be noted that it has been assumed the truck position time is taken as starting the moment a truck is able to do so; this time is either the moment the previous truck has finished discharging or when a truck arrives on site, depending on the status of the queue.

Now consider Table III, which has a summary of all the key observed characteristics for the 202 concrete pours. These have been broken down into sub-projects and the type of pour involved.

<table>
<thead>
<tr>
<th>Events</th>
<th>Observed</th>
<th>Characteristics</th>
<th>Calculated characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time concrete is batched</td>
<td>Number of trucks</td>
<td>Truck utilization</td>
<td></td>
</tr>
<tr>
<td>Time truck arrives on site</td>
<td>Number of pumps</td>
<td>Pump utilization</td>
<td></td>
</tr>
<tr>
<td>Time truck becomes idle</td>
<td>Truck capacity</td>
<td>Truck cycle time</td>
<td></td>
</tr>
<tr>
<td>Time truck starts to discharge concrete</td>
<td>Concrete volume</td>
<td>Truck idle time</td>
<td></td>
</tr>
<tr>
<td>Time truck finishes discharging</td>
<td>Concrete slump</td>
<td>Truck interarrival time</td>
<td></td>
</tr>
<tr>
<td>Time taken to wash truck</td>
<td>Distance travelled by truck</td>
<td>Truck position time</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pump time</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pump idle time</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Truck travel time</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cycles per working hour</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operation duration</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rejection rate</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum possible production</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Actual production</td>
<td></td>
</tr>
</tbody>
</table>
TABLE III  Numbers and Types of Pour, Sizes and Durations for All Pours Observed.

<table>
<thead>
<tr>
<th>Job</th>
<th>Type of pour</th>
<th>Number of pours</th>
<th>Mean pour size (m$^3$)</th>
<th>Mean pour duration (mins)</th>
<th>Mean truck-mixer volume (m$^3$)</th>
<th>Mean number of trucks on pour</th>
<th>Mean cycle time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wall</td>
<td>1</td>
<td>23.5</td>
<td>167.5</td>
<td>6.7</td>
<td>2.2</td>
<td>55.2</td>
</tr>
<tr>
<td></td>
<td>Column</td>
<td>4</td>
<td>88.0</td>
<td>343.0</td>
<td>7.3</td>
<td>4.0</td>
<td>91.6</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>5</td>
<td>251.4</td>
<td>639.2</td>
<td>7.5</td>
<td>6.4</td>
<td>81.0</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>10</td>
<td>143.9</td>
<td>420.9</td>
<td>7.2</td>
<td>4.5</td>
<td>76.0</td>
</tr>
<tr>
<td>2</td>
<td>Wall</td>
<td>9</td>
<td>52.0</td>
<td>253.0</td>
<td>7.2</td>
<td>4.2</td>
<td>121.9</td>
</tr>
<tr>
<td></td>
<td>Column</td>
<td>2</td>
<td>66.5</td>
<td>329.5</td>
<td>6.8</td>
<td>5.5</td>
<td>130.0</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>9</td>
<td>241.5</td>
<td>538.9</td>
<td>7.2</td>
<td>7.8</td>
<td>96.8</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>20</td>
<td>138.7</td>
<td>389.3</td>
<td>7.2</td>
<td>6.0</td>
<td>111.4</td>
</tr>
<tr>
<td>3</td>
<td>Wall</td>
<td>104</td>
<td>46.7</td>
<td>250.4</td>
<td>7.4</td>
<td>2.8</td>
<td>81.1</td>
</tr>
<tr>
<td></td>
<td>Column</td>
<td>15</td>
<td>34.4</td>
<td>178.1</td>
<td>7.1</td>
<td>2.7</td>
<td>54.0</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>53</td>
<td>81.8</td>
<td>270.3</td>
<td>7.6</td>
<td>3.5</td>
<td>69.1</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>172</td>
<td>56.4</td>
<td>250.2</td>
<td>7.4</td>
<td>3.0</td>
<td>75.0</td>
</tr>
<tr>
<td>All pours</td>
<td></td>
<td>202</td>
<td>68.9</td>
<td>272.4</td>
<td>7.4</td>
<td>3.4</td>
<td>78.7</td>
</tr>
</tbody>
</table>
For the three sub-projects observed each has been divided into wall, column and base pours due to the differences between the planning of each. The mean pour size in the sample was 68.9 m$^3$, reflecting the amount of wall and column pours observed (67% of all pours). One-quarter of the sample consisted of pours smaller than 32 m$^3$ and one-quarter were greater than 66 m$^3$. The results found in this paper therefore represent the smaller end of concrete pours, which present their own planning and scheduling problems due to their abundance and fragmented nature.

The mean duration of all pours was found to be 272 minutes (approximately 4.5 hours), with one-quarter of the pours being less than 180 minutes (3 hours) and one-quarter being greater than 340 minutes (5 hours 40 minutes). The type of pours observed on-site can explain these durations. Wall and column pours have to be poured in a controlled manner and while they may not be a large pour in terms of volume, they can often take a substantial amount of time. In this study, the mean duration for wall and column pours combined was found to be 242 minutes (4 hours 2 minutes) for a total mean volume of 46 m$^3$ compared to 334 minutes (5 hours 34 minutes) for a total mean volume of 116 m$^3$ for all base pours.

**PERFORMANCE ANALYSIS ON OBSERVED DATA**

**Productivities Being Achieved**

For the sample of pours, it was possible to calculate the actual productivity measured in m$^3$/hour, Table IV.

Concentrating on the overall actual productivity for the sample, it is possible to differentiate between the three types of structures encountered. Firstly, it is evident that wall and column pours are related in many ways. The volume of concrete being placed is similar and the productivity rates achieved are similar ($\sim$11 m$^3$/hr) and reflect the way in which they are poured. Wall and column structures have to be placed in a controlled manner due to their shape so that no structural damage or weakness occurs. This reduces the productivity rates and will result in less trucks being assigned to these particular pours. For base pours the

<table>
<thead>
<tr>
<th>Sub-project</th>
<th>Type of pour</th>
<th>Number of pours</th>
<th>Mean pour size (m$^3$)</th>
<th>Mean measured actual productivities (m$^3$/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wall</td>
<td>1</td>
<td>23.5</td>
<td>15.4</td>
</tr>
<tr>
<td></td>
<td>Column</td>
<td>4</td>
<td>88.0</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>5</td>
<td>251.4</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>10</td>
<td>143.9</td>
<td>16.9</td>
</tr>
<tr>
<td>2</td>
<td>Wall</td>
<td>9</td>
<td>52.0</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>Column</td>
<td>2</td>
<td>66.5</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>9</td>
<td>241.5</td>
<td>26.0</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>20</td>
<td>138.7</td>
<td>18.4</td>
</tr>
<tr>
<td>3</td>
<td>Wall</td>
<td>104</td>
<td>46.7</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>Column</td>
<td>15</td>
<td>34.4</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>53</td>
<td>81.8</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>172</td>
<td>56.4</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>All wall</td>
<td>114</td>
<td>47.5</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>All column</td>
<td>21</td>
<td>35.4</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>All base</td>
<td>67</td>
<td>116.0</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>All pours</td>
<td>202</td>
<td>68.9</td>
<td>13.6</td>
</tr>
</tbody>
</table>
The mean volume of concrete being placed was 116 m$^3$ and a higher productivity rate of 18.5 m$^3$/hr was achieved.

The nature of base pours result in concrete being placed as fast as possible and therefore the overall productivity of an operation should mirror the capacity of the concrete pump. For the three projects in the sample the same concrete pump was used and from the manufacturer's specifications it was claimed to have a maximum capacity of 160 m$^3$/hr. This obviously does not mirror the actual productivity found on base pours, and would not, due to the limited capacity of truck mixers (typically 6–8 m$^3$) and the variability within the system. It does however raise a case for an increase in truck mixer capacity, which would decrease the amount of truck changes in an operation.

For the sample, containing 202 pours and having an average pour size of 69 m$^3$, a mean productivity rate of 13.6 m$^3$/hr was found. Some comparable figures for pumping in the UK, West Germany and Hong Kong are available (Anson et al. 1989; Anson and Wang, 1998). The UK based study had a mean pour size of 92 m$^3$ and a placing speed of 15.5 m$^3$/hr, the West German study had a mean pour size of 170 m$^3$ and a placing speed of 20.5 m$^3$/hr and the Hong Kong based study had a mean pour size of 144 m$^3$ and a placing speed of 21.4 m$^3$/hr. The UK sample numbered 70, the West German sample numbered 32 and the Hong Kong based sample numbered 51 pours. These rates compare well with those found in this study, however it is very difficult to say which country's industry is performing better due to the variations in types of pour, pour size and number of pours in the sample.

Observed Pump Idle Times

If we consider Table V, we can see the pump idle time calculated from the four events recorded on site (columns 3–6), as well as the cost of pump idle times (column 10) for the observed concrete pours. All costs have been taken from a major civil engineering contractor's estimating department, so they do reflect the current practices in the UK construction industry.

If we consider the data in Table V, it is possible to see that for all 202 pours the average total pump idle time is 51 minutes per pour. This could be considered high and results in large delays to concrete operations. However, when presented to the contractor's management team it was taken as an expected value and they were prepared to tolerate such a waste. The same finding was then transferred into a cost estimate using their cost estimations. The resulting waste of £1.13/m$^3$ was taken seriously. For the three sub-projects in the sample the total cost of pump idleness was found to be £15,750. In today's globally competitive market this financial waste cannot be tolerated.

As previously mentioned the truck positioning time is seen as a necessary delay, however as we can see from column 5 in Table V this is calculated to represent approximately 13 minutes of each pour. This leaves an average of 34 minutes of non-tolerable waste.

Observed Truck Idle Times

If we again consider Table V, for all pours, it can be seen that there is an average of 35.8 minutes of truck idleness on every pour. This appears to be quite large, and does result in 'hidden' costs to the contractor. On average it has been calculated that during the course of a concrete pour costs of £0.20/m$^3$, of concrete delivered, can be incurred by the contractor due to trucks being idle on site. Even though this is significantly less than the cost of an idle pump it still accounts for £2790 over the whole project observed, which would have been better used in providing tools to overcome these issues.
### TABLE V  
Time Observations on Site and Cost of Idle Times (Cost Data is Taken from a Contractors Estimating Department)

<table>
<thead>
<tr>
<th>Job</th>
<th>Type of pour</th>
<th>Mean truck inter-arrival time (mins)</th>
<th>Mean truck wait time (mins)</th>
<th>Mean position time at pump (mins)</th>
<th>Mean truck pump time (mins)</th>
<th>Mean total truck idle time on site (mins)</th>
<th>Mean total pump idle time (mins)</th>
<th>Mean cost to contractor of truck idle time (£/m³)</th>
<th>Mean cost to contractor of pump idle time (£/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wall</td>
<td>27.0</td>
<td>8.0</td>
<td>8.0</td>
<td>18.0</td>
<td>48.0</td>
<td>47.0</td>
<td>0.77</td>
<td>3.06</td>
</tr>
<tr>
<td></td>
<td>Column</td>
<td>52.0</td>
<td>0.0</td>
<td>35.5</td>
<td>15.0</td>
<td>0.0</td>
<td>65.7</td>
<td>0.0</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>17.2</td>
<td>7.2</td>
<td>5.2</td>
<td>12.0</td>
<td>198.0</td>
<td>67.6</td>
<td>0.30</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>32.1</td>
<td>4.4</td>
<td>17.6</td>
<td>13.8</td>
<td>104.2</td>
<td>64.8</td>
<td>0.27</td>
<td>0.68</td>
</tr>
<tr>
<td>2</td>
<td>Wall</td>
<td>33.8</td>
<td>12.8</td>
<td>11.4</td>
<td>19.3</td>
<td>40.1</td>
<td>56.0</td>
<td>0.29</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>Column</td>
<td>32.5</td>
<td>31.0</td>
<td>6.0</td>
<td>26.5</td>
<td>172.5</td>
<td>15.0</td>
<td>0.97</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>15.3</td>
<td>8.1</td>
<td>5.7</td>
<td>9.4</td>
<td>181.0</td>
<td>68.0</td>
<td>0.28</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>25.3</td>
<td>12.5</td>
<td>8.3</td>
<td>15.6</td>
<td>116.7</td>
<td>57.3</td>
<td>0.32</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>Wall</td>
<td>39.5</td>
<td>6.9</td>
<td>14.5</td>
<td>22.6</td>
<td>14.5</td>
<td>52.8</td>
<td>0.12</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>Column</td>
<td>36.0</td>
<td>7.9</td>
<td>12.5</td>
<td>22.1</td>
<td>14.5</td>
<td>28.8</td>
<td>0.16</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>28.3</td>
<td>4.7</td>
<td>10.1</td>
<td>16.7</td>
<td>40.2</td>
<td>48.8</td>
<td>0.18</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>35.7</td>
<td>6.3</td>
<td>12.97</td>
<td>20.7</td>
<td>22.4</td>
<td>49.5</td>
<td>0.15</td>
<td>1.34</td>
</tr>
<tr>
<td>All pours</td>
<td></td>
<td>34.5</td>
<td>6.9</td>
<td>12.74</td>
<td>19.86</td>
<td>35.8</td>
<td>51.0</td>
<td>0.20</td>
<td>1.13</td>
</tr>
</tbody>
</table>
Regression Analysis

Regression analysis is a powerful tool that enables the researcher to learn more about the relationships within the data being studied and has been used by various researchers (e.g. Smith, 1999b). It is one of the most widely used statistical tools because it provides a simple method for establishing a functional relationship among variables. There are many texts that describe this technique (e.g. Hogg and Ledolter, 1992), and the theory behind its use will not be discussed in detail here.

In this instance multiple linear regression will be used to determine the statistical relationship between a response (e.g. actual productivity) and the explanatory variables (e.g. number of trucks used or type of pour).

The regression model requires a few assumptions to be made. It is of the form: 
\[ y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \ldots + \beta_p x_{pi} + e_i, \]
where \( i = 1, 2, 3, \ldots, n \) and assumes the following:

- \( y_i \) is the response that corresponds to the levels of the explanatory variables \( x_1, x_2, \ldots, x_p \) at the \( i \)th observation.
- \( \beta_0, \beta_1, \beta_2, \ldots, \beta_p \) are the coefficients in the linear relationship. For a single factor \( (p = 1) \), \( \beta_0 \) is the intercept, and \( \beta_1 \) is the slope of the straight line defined.
- \( e_1, e_2, \ldots, e_n \) are errors that create scatter around the linear relationship at each of the \( i = 1 \) to \( n \) observations. The regression model assumes that these errors are mutually independent, normally distributed, and with a zero mean and variance \( \sigma^2 \). It is important that this constant variance assumption holds, but in reality this is sometimes difficult to achieve.

To make estimates of the coefficients in the regression model, the method of least squares is used by virtue of its simplicity.

Regression Analysis and the Explanatory Variables

The main purpose of carrying out a regression analysis on the observed data is to obtain a model that will estimate productivity rates of concrete operations. By achieving this it will help planners and estimators to make allowances and hence better the overall performance of concrete operations.

The regression analysis methodology used in this study is backward elimination, stepwise regression. The study begins with a full set of explanatory variables in the model and eliminates ‘non-significant’ variables one at a time until all the remaining variables are ‘significant’. At any step the variable with the smallest absolute \( t \)-statistic, that is the ratio of the co-efficient to its standard error, will be eliminated; a large \( t \)-ratio is therefore desirable. The critical \( t \)-ratio, at a significance of 5\%, is \( t(0.025; n - p - 1) = 1.98 \), where \( n \) is the number of observations in the sample (202), and \( p \) is the number of explanatory variables (9). This implies that all variables with an absolute \( t \)-ratio <1.98 are not significant to the regression model.

In addition, the \( F \)-ratio may be used to test for the significance of the overall dependence of \( y \) on the variables \( x_1, x_2, \ldots, x_p \). It is defined as the ratio of the regression mean square to the residual mean square. It provides a way of examining whether \( \beta_1 \) is equal to zero or not.

- If \( F > F(x; p, n - p - 1) \), \( \beta_1 \neq 0 \); this means that \( X \) provides significant information for predicting \( Y \).
- If \( F < F(x; p, n - p - 1) \), \( \beta_1 = 0 \); this means that \( X \) provides little or no help in predicting \( Y \).
For this regression analysis the critical F-ratio at a significance level of 1%, \( F(0.01, 8, 192) \), is found to be 2.53.

When carrying out a multiple linear regression analysis it is important to identify all explanatory variables that are thought to account for much of the variability in concrete operations. The explanatory variables that were thought to be important by the investigator are:

- **Type of pour** (wall = 1, column = 2 and base = 3). The type of pour will reflect the general size and shape of the structural element to be cast – for example a base pour will have a very low depth to height ratio when compared to a column and this will result in differences in the exact casting method used. There are a variety of ways in which this difference could be explained, for example in using the actual size of the elements, but such details may not be known at all planning stages.

- **Total volume** (\( m^3 \)) is the volume of the element which is being cast in one separate operation. Some large elements, such as walls, may be poured and cast in separate operations and the **Total Volume** must not be the overall volume of the element.

- **Number of trucks on job**. This is the number of separate truck-mixers used, i.e. the fleet size, which usually provide multiple loads. It is not the number of loads delivered.

- **Av. Volume of load** (\( m^3 \)). Many truck-mixers have a nominal capacity of 6 \( m^3 \), but other capacities may be used. This is the average taken from all delivered loads. The volume has been measured as that ordered and quoted on the delivery ticket. Whilst in actuality this volume may be slightly different due to quality control procedures, there is no practical method of accounting for this.

- **Start time** (before 6 am, 6 am–9 am, 9 am–12 pm, 12 pm–3 pm, 3 pm–6 pm or after 6 pm). The time when the first load arrives on site, rather than when it was batched.

- **Number of loads**. The number of individual loads delivered from all truck-mixers.

- **Weather** (Overcast, Sunny, Rain, Cold and Clear or Snow). Quantifying weather is a very difficult task and, when using data collected by a variety of people, may be subjective also. It is considered that these five categories are both objective and typical of possible UK conditions.

- **Average truck cycle time** (minutes). The time that one truck-mixer takes to be batched, travel, discharge, washout and return to batching plant. The start and end points can be taken at any point on the cycle.

- **Concrete mix** (C40/20 Pfac Pump, C35A/20 Pfac Pump, C50/10 Pc Pump, C35/10 S/pl). On the operations observed, these are the four mix designs used. If this explanatory variable is significant, the model would not be able to be used for other mixes.

The investigators acknowledge that the selected explanatory variables may not represent a definitive list.

The first step in the analysis of these data is to make a careful study of what it is that these variables are measuring, noting any highly correlated pairs. The correlation coefficients between all possible pairs can be determined in a number of ways but it is convenient to use the in-built functions of Microsoft Excel, which can produce them very easily. This was done and the correlation coefficients between the pairs are shown in Table VI.

As a rule, explanatory variables in multiple regression are correlated, and if the correlation coefficient (positive or negative) is high then it becomes difficult, without very large samples, to disentangle their separate effects on the response. A high correlation coefficient will ultimately lead to a poorly estimated partial regression coefficient.

In Table VI it can be seen that in this case there is very high correlation between total volume and the number of loads in the operation (highlighted). If we plot the number of loads against total volume, as seen in Figure 2, we can see that there is a very strong linear
<table>
<thead>
<tr>
<th>Type of pour</th>
<th>Av. volume</th>
<th>No. of trucks on job</th>
<th>Av. cycle time</th>
<th>Concrete mix</th>
<th>Weather</th>
<th>Start time</th>
<th>No. of loads</th>
<th>Total volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of pour</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Av. volume</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of trucks on job</td>
<td>0.36</td>
<td>0.09</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Av. cycle time</td>
<td>-0.15</td>
<td>0.19</td>
<td>0.34</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete mix</td>
<td>-0.16</td>
<td>0.11</td>
<td>-0.38</td>
<td>-0.26</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weather</td>
<td>0.11</td>
<td>0.19</td>
<td>0.15</td>
<td>0.07</td>
<td>0.00</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start time</td>
<td>-0.38</td>
<td>-0.07</td>
<td>-0.23</td>
<td>-0.10</td>
<td>0.07</td>
<td>-0.17</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>No. of loads</td>
<td>0.48</td>
<td>0.16</td>
<td>0.79</td>
<td>0.26</td>
<td>-0.34</td>
<td>0.20</td>
<td>-0.41</td>
<td>1.00</td>
</tr>
<tr>
<td>Total volume</td>
<td>0.49</td>
<td>0.22</td>
<td>0.78</td>
<td>0.26</td>
<td>-0.32</td>
<td>0.21</td>
<td>-0.42</td>
<td>0.99</td>
</tr>
</tbody>
</table>
relationship, $R = 0.99$. As mentioned this will lead to poorly determined estimates of their partial regression coefficients and difficulty in interpreting the effects of the explanatory variables on the response. This is a simple case of what is more commonly known as the problem of multicollinearity and must be addressed before the study can go any further. Stepwise regression assumes a number of conditions to be adhered to. One of these is that there is no serious near-multicollinearity in the data. Since there will be no advantage of having both variables in the regression (one can represent the other) a decision has been made to remove ‘total volume’ from the regression in order to maximise the reliability of the final models.

Backward Stepwise Regression on the Observed Data

Having determined the explanatory variables to be considered and having conducted tests to discover if any linear relationships exist between the variables the regression analysis can commence. All results will be tabulated in the form of an analysis of variance (ANOVA) table and will show, where appropriate, the results for the first and final runs of the regression.

First of all it is important to recap on some of the critical values relevant to the analysis and introduce some new criteria. These will help to provide reliable and statistically correct models.

- Critical $t$-statistic is 1.98. Therefore any variable with a $t$-statistic $> 1.98$ will be significant.

REGRESSION ON ACTUAL PRODUCTIVITY

Table VII shows the estimated partial regression coefficients and the corresponding $t$-statistics from the regression on actual productivity for all eight explanatory variables. As can be seen the $t$-ratios are all relatively large and this is reflected by the $R^2_{adj}$ value for the first run of 0.8066 and the $F$-ratio of 105.76 shown in Table VIII. However, it will be necessary to carry out two further runs, eliminating the insignificant variables: concrete mix ($t$-statistic $= -0.97$) and the start time ($t$-statistic $= 1.72$) from the regression model.

For actual productivity it was only necessary to carry out three runs of regression before all criteria were satisfied and the model was proven to be significant. From the original set of
TABLE VII Correlation Coefficients Between All Pairs of the 10 Explanatory Estimated Partial Regression Coefficients and the Corresponding t-Statistics from the Regression on Actual Productivity for All Nine Explanatory Variables – Run 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>t-stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-7.57</td>
<td>-3.48</td>
</tr>
<tr>
<td>Type of pour</td>
<td>1.39</td>
<td>6.06</td>
</tr>
<tr>
<td>Av. volume</td>
<td>1.78</td>
<td>6.40</td>
</tr>
<tr>
<td>No. of trucks on job</td>
<td>0.47</td>
<td>2.57</td>
</tr>
<tr>
<td>Av. cycle time</td>
<td>-0.01</td>
<td>-2.42</td>
</tr>
<tr>
<td>Mix</td>
<td>-0.36</td>
<td>-0.97</td>
</tr>
<tr>
<td>Weather</td>
<td>0.63</td>
<td>3.50</td>
</tr>
<tr>
<td>Start time</td>
<td>0.32</td>
<td>1.72</td>
</tr>
<tr>
<td>No. of loads</td>
<td>0.39</td>
<td>10.2</td>
</tr>
</tbody>
</table>

TABLE VIII ANOVA Statistics for Regression on Actual Productivity – Final Run 1.

<table>
<thead>
<tr>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>8</td>
<td>4805.89</td>
<td>600.74</td>
</tr>
<tr>
<td>Residual</td>
<td>193</td>
<td>1096.32</td>
<td>5.68</td>
</tr>
<tr>
<td>Total</td>
<td>201</td>
<td>5902.21</td>
<td></td>
</tr>
<tr>
<td>$R^2_{adj}$</td>
<td></td>
<td>80.66%</td>
<td></td>
</tr>
</tbody>
</table>

nine explanatory variables it was necessary to remove the start time and the concrete mix. Table IX shows the coefficients and statistics for the final run. It is also possible to show, from Table X, that the $F$-ratio is 107.9, which is much greater than the critical $F$-ratio of 2.53.

As a further indication of how the regression equation fits the data, consider the plot in Figure 3. When the actual productivity values are plotted against the values derived from the regression equation, a linear trend with close fit is obtained; the estimate of a point that lays on the 1:1 line is exactly equal to the observed value of actual productivity.

Although it has been determined that there is a significant regression equation for actual productivity, it is important that the assumptions of the regression model are satisfied. One of the most important assumptions is that the variability of the data does not change for different levels of the response or explanatory variables. One way to check this is to carry out residual plots.

The residual $e_i$ is the difference between the observed response $y_i$ and the estimated or fitted value $\hat{y}_i$. If the constant variance assumption holds true, then residuals will follow an
TABLE X ANOVA Statistics for Regression on Actual Productivity – Final Run.

<table>
<thead>
<tr>
<th></th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>6</td>
<td>4782.30</td>
<td>797.05</td>
<td>138.78</td>
</tr>
<tr>
<td>Residual</td>
<td>195</td>
<td>1119.91</td>
<td>5.74</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>201</td>
<td>5902.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2_{adj}$</td>
<td>80.44%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$N(0, \sigma^2)$ distribution and a plot of the residuals for each $i$ against the fitted values $\hat{y}_i$ should follow a random pattern, with 95% of the points lying within a $2\sigma$ horizontal band around zero.

In Figure 4, the residuals from the final run of the regression analysis are plotted against fitted values of the regression equation; no non-random pattern can be detected. As the mean square of the residual in the ANOVA is an estimator for $\sigma^2$, it can be determined from Table X that most of the residuals should fall between $\pm 2\sqrt{5.5868}$ or $\pm 4.727$. It is clear from
Figure 4 that this is indeed the case (approximately 8 points lie outside this range, or 4% of the total observations) concluding that the constant variance assumption is satisfied.

**DERIVED MODEL OF ACTUAL PRODUCTIVITY**

Finally, a multiple linear regression model can be given for actual productivity for a single server concrete system can be given as follows

\[
P_{\text{actual}} = 1.31T_p + 1.75V_a + 0.56T_n + 0.59W - 0.01C_t + 0.37L_n - 6.95
\]

where \( T_p \) = Type of pour
\( V_a \) = Average volume of concrete
\( T_n \) = Number of trucks on job
\( W \) = Weather
\( C_t \) = Average cycle time
\( L_n \) = Number of loads

**VALIDATION OF DERIVED MODEL**

In order for this to be of practical use on construction projects it must first be validated. For the purpose of this study the regression model is validated using actual concrete pours from another wastewater project in the Scotland (Project B). As a different contractor managed the project it will be interesting to discover if the developed model will be valid. All pours were poured using the same methods and placing procedures and planning as in Project A.

The actual productivities achieved on 32 operations observed on Project B are compared to the predicted productivities using the derived regression model; these 32 comparisons can be seen in Figure 5. The plot reveals an interesting trend and it can be seen that there are several significantly different areas or zones.

![Figure 5](image)

**FIGURE 5** Plot showing predicted and actual productivity of pours on project used for validation.
Pours 1 to 9 (Zone 1, Fig. 5) probably provide the least accurate predictions using the model. This may be due to a number of reasons:

- Firstly, these pours represent those pours with low probability rates (approx. 6 m³/h) and the model appears to overestimate the productivities. The fact that the productivity of these pours is so low may be due to unforeseen occurrences in the delivery or placement of the concrete occurrences which are not allowed for within the model's explanatory variables.
- The data-set used to derive the regression model (from Project A) had a very similar range of productivities (4.8 to 31 m³/hr) to that observed on Project B (4.3 to 32.8 m³/hr). However, Project A's data-set contained only 3% of pours with productivities less than 6 m³/hr - Project B has 28% of pours below this point. Consequently the derived model will be poor at predicting productivities at such low levels.
- Three of Zone 1's low productivities can be accounted for by poor quality concrete arriving on site. The concrete has been rejected due to its poor workability and the concrete pump has been idle until the next load has arrived; this increases the length of the overall pour and hence decreases the productivity.
- Most of Zone 1 operations are wall or column pours and these return low productivities due to the nature in which they have to be poured, for example, high narrow column structures would have to be poured in a slow controlled manner. The regression model, however, can only allow for the general type of pour (wall, column, base) and cannot model more specific characteristics of the pour shape.
- Two of the operations in Zone 1, pours 6 and 9, are base pours and the model overestimates their productivities by 48 and 50%. The actual productivities are low for these base pours; on observation of the original data it was seen that these pours did not conform to the typical high volume/high productivity nature of base pour operations.

The next zone (Zone 2, Fig. 5) concerns pours 10 to 27, which show encouraging predictions using the regression model. The 17 pours return an average of only 11.4% difference in the predicted and actual productivities. The 17 pours are primarily made up of wall pours and show that the model appears to be accurate when dealing with pours in this range.

The final zone (Zone 3, Fig. 5) is solely made up of base pours (pours 28 to 32). Base pours do yield the highest productivities due to the speed at which they can be poured. The percentage difference between the predicted and actual productivities in this zone is 12% and it can be seen that the model underestimates all of these pours.

CONCLUSIONS

This paper has presented and discussed some of the key characteristics in concrete operations including productivity, truck idleness and pump idleness. A multiple linear regression analysis was also undertaken to develop a model for productivity with some very favourable findings.

With any regression analysis, which shows statistically good results, it is sometimes tempting to blindly use the regression model in all situations. The regression model for actual productivity, which has been undertaken and described in this paper, has provided a model that describes over 80% of the variability in the data set collected of observed concrete operations. The significant factors (in order of importance) are as follows: number of loads, average volume, type of pour, weather, number of trucks on job and the average cycle time. However, it does not imply that other factors cannot influence the productivity
of concrete operations; any estimating tasks should always allow for those instances when normal operating conditions do not apply.

The data for the regression model were based on one major project in the North-East of Scotland involving a collaboration of contractors. A question arose as to whether the developed model could be used in projects managed by different contractors. In the validation of the model this was indeed shown to be the case: the model produced some favourable predictions of productivity when results from actual concrete pours from a different project, undertaken by a different contractor, were applied.

Finally, the validation exercise demonstrated that the model derived for estimating actual concrete productivity produces good results for productivities greater than approximately 6 m$^3$/hr. In the data set used for the validation exercise (Project B) this coincided with pours which were wall or base pours. The model was seen to be quite poor at predicting productivities less than 6 m$^3$/hr.

References


SIMULATION ANALYSIS OF THE UK CONCRETE DELIVERY AND PLACEMENT PROCESS – A TOOL FOR PLANNERS

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The UK construction industry continually strives to improve previous performance and increase financial efficiency in terms of labour, plant and materials. Construction projects are very rarely made up of one activity or process and in most cases projects involve a multitude of task specific and intricate processes. In order to achieve desired goals, such as better productivity rates, it is fundamental that an improvement is witnessed in the performance of each and every process.

One such process is the delivery and placement of ready-mixed concrete. Evident in the vast majority of major civil engineering projects in the UK, concrete is a very valuable material, and one that requires meticulous planning in order to successfully get it to site and into the required formwork. The successful completion of many construction projects, on time and within budget, can be decided by the effectiveness of the concreting phase. So, therefore, why in the UK are very few tools available for the efficient planning and completion of concrete operations?

It is proposed that by using simulation to model the concrete process it will be possible to plan and manage productivity rates of concrete operations. The factors that influence the concrete system can be summarised as: truck mixer interarrival time, truck mixer position time, concrete load pump time and truck mixer volume. This paper will look at a model of the above factors, based on over 300 'real' concrete pours. The random variability of these factors can be incorporated into a model by using the gamma probability distribution for the interarrival time, the exponential probability function for the position time and finally the inverse Gaussian probability distribution for the pump time. The development of the model and the simulation runs carried out will be described. The main results of the experimental process will aid planners in optimising the concrete process by maximising productivity and minimising cost.

Keywords: concrete operations, cyclic construction processes, Monte Carlo simulation, probability distribution functions

INTRODUCTION

The UK construction industry is continually striving to improve previous performance and increase financial efficiency in terms of labour, plant and materials. The realisation that this has to be done has been apparent for many years; now, due to increasing global competition within the industry, it is one that is finally being embraced. Latham (1994) in his review suggested that productivity improvements in the UK of up to 30% were necessary to face the challenges of the next millennium. Egan (1998) added to this building on Dunlop, P.G. and Smith, S.D. (2002) Discrete-Event Simulation Analysis Of The Current UK Concrete Delivery And Placement Process – A Tool For Planners. ARCOM 18th annual conference. University of Northumbria, Newcastle, Sept 2-4. 781-790.
Latham’s earlier work and suggested that productivity be increased by 10% per year. At the time of this report productivity was increasing by an average of 5% per year with the best projects demonstrating increases of up to 15%. These figures reflect the current improvements in the UK construction industry today, though there is still room for further improvements.

Construction projects are complex: they are very rarely made up of one activity or process and in most cases they involve a multitude of task specific and intricate processes. In order to achieve desired goals, such as better productivity rates, it is fundamental that an improvement is witnessed in the performance of each and every process. One such process is that of ready mixed concrete delivery and placement, which is common to many of the UK’s construction projects. The successful execution of this process is essential if a project is to be managed efficiently due to the high cost of not only the material but also the labour and plant used.

In order to achieve this it is useful to study past UK concrete pour records and make improvements on some key aspects. The concreting process has in the past been subjected to much research (Anson 1989, 1998 and Smith 1998, 1999), however the findings may have been geographically specific and little has been carried out in the UK. Although this work has been published on the subject of modelling the concreting process few contractors in the UK seem to use such methods and continue to resource and plan their concreting contracts using the experience from past projects. This paper will outline a computer based simulation, using probability distributions, which can be used at both the tender and implementation stage as an estimation and planning tool. The developed simulation is based on the study and observation of nearly 400 “real” UK concrete pours spread over 6 multi-million pound projects.

THE CONCRETE DELIVERY AND PLACEMENT PROCESS EXPLAINED

Concrete is a complex material and due to its short shelf life it is important that careful consideration of concrete supplier is made. In the UK, it is usual that the concrete supplier will transport the concrete to the required site using his own truck mixers under instructions by the contractor, such as delivery time, dispatch time between trucks etc. These instructions are often not carefully planned and by simulating concrete processes it may be possible to be more accurate with these.

Figure 1 shows a flow diagram of the concrete process. It can be seen that it consists of two distinct cycles: one at the batching plant and one on the construction site. Both of these are cyclic and can be treated as single server queuing systems. A queuing system is characterised by three components: arrival process, service mechanism, and queue discipline. Specifying the arrival process for a queuing system consists of describing how customers arrive to the system. The service mechanism for a queuing system is articulated by specifying the number of servers, whether each server has its own queue or there is one queue feeding all servers, and the probability distribution of customers’ service times. For the purpose of this paper it is assumed that only one server is available. The queue discipline of a queuing system refers to the rule that a server uses to choose the next customer from the queue (if any) when the server

completes the service of the current customer (Law and Kelton 1991). In the case of concrete operations customers are normally served in a first-in, first-out manner (FIFO) due to the nature of concrete's shelf life.

For a detailed description of the concreting process see Dunlop and Smith (2000).

**Figure 1: Flow diagram of the concrete process**

**MODEL FOR INVESTIGATION**

Due to the constraints of this paper, no detailed account of the batching process will be given in the simulation model. If figure 1 is simplified, as in figure 2, the model will only deal with events that take place on the construction site.

As with all modelling exercises, whether physical or numerical, the main aim of this study is to represent the concreting system in a way that can be investigated.

practically, economically and safely. The real concreting process is a very expensive undertaking, which limits the amount by which the underlying relationships in the process can be determined. If a model of the system is valid, i.e., it represents satisfactorily the real system; results obtained via the model can be interpreted and applied to a real situation with confidence.

Data Collection
In order to produce a valid model it is essential to investigate the nature of the real system. Data was collected from 6 different projects from a total of 396 separate concrete pours. Each pour used a concrete pump as the placing method. Details of the 6 projects can be seen in Table 1.

Table 1: Details of studied projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Year of completion</th>
<th>Type of project</th>
<th>Location</th>
<th>Number of concrete pours observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1994</td>
<td>Motorway viaduct strengthening and widening</td>
<td>Cheshire, England</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
<td>Wastewater treatment plant</td>
<td>Dundee, Scotland</td>
<td>54</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>Wastewater treatment plant</td>
<td>Aberdeen, Scotland</td>
<td>202</td>
</tr>
<tr>
<td>4</td>
<td>In progress</td>
<td>Transportation</td>
<td>Falkirk, Scotland</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>2001</td>
<td>Wastewater treatment plant</td>
<td>Inverness, Scotland</td>
<td>29</td>
</tr>
</tbody>
</table>

Table 2 shows the statistics that have been derived from the data, giving the interarrival time (i.e. the lapsed time between truck mixer arrivals), the position time (i.e. the time the truck mixer takes to move from the queue, position itself at the hopper of the pump and prepare itself for unloading) and the pump time.

Table 2: Summary of the data gathered from the observed projects

<table>
<thead>
<tr>
<th></th>
<th>Interarrival time /secs</th>
<th>Position time /secs</th>
<th>Pump time /secs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1215</td>
<td>435</td>
<td>796</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1013</td>
<td>572</td>
<td>580</td>
</tr>
<tr>
<td>No. of Observations</td>
<td>4692</td>
<td>4679</td>
<td>5077</td>
</tr>
</tbody>
</table>

Probability Distribution Functions
In order to carry out a simulation using random inputs such as interarrival times, their probability distributions have to be specified. Pritsker (1995) defined probability distributions as "any rule which assigns a probability to each possible value of a random variable." In this case, theoretical distributions are being used to represent the observed data, namely interarrival, position and pump times and to level any data irregularities that may have been derived from the observations.

The data, collated from the time studies, is used to fit a theoretical distribution using heuristic procedures or goodness-of-fit techniques. These smooth irregularities of an empirical distribution, allowing the possibility of sampling extreme values, and represents the most compact and timesaving procedure for performing simulations (Law and Kelton 1991).

Computer software programs have been developed that automatically assess the goodness-of-fit of observed data to theoretical distribution functions. The program Bestfit is used in this study. Bestfit compares the observed data to 26 different distributions (Bestfit 1993). With the Bestfit program the parameters

for each theoretical distribution are compared to the sample data using maximum likelihood estimators; then they are optimised and the chi-square, the Kolmogorov-Smirnov (K-S), and the Anderson-Darling (A-D) goodness-of-fit test statistics are calculated. Table 3, shows only the valid distributions from the 26 tested using the Bestfit software for the three input data. The initial test involved a visual analysis and from this it was possible to eliminate distributions with a poor fit. Each distribution was then ranked using the chi-squared, K-S and A-D test statistics. For each of the distributions tested the lower boundary was set to zero (that is, it is impossible to have a negative time value) which immediately eliminates certain distributions.

### Table 3: Ranked valid distributions for the three input data sets

<table>
<thead>
<tr>
<th>Input</th>
<th>Valid distributions</th>
<th>Chi-squared Rank</th>
<th>A-D Rank</th>
<th>K-S Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interarrival time</td>
<td>Erlang</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Exponential</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rayleigh</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Position time</td>
<td>Gamma</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Exponential</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Erlang</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Rayleigh</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Pump time</td>
<td>Pearson VI</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Loglogistic</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Lognormal 2</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Inverse Gaussian</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Pearson V</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Exponential</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
<td>7</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Erlang</td>
<td>8</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Weibull</td>
<td>9</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Rayleigh</td>
<td>10</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

It can be seen that the ranks according to the three separate goodness-of-fit tests are markedly different: which test to use? All three have unique advantages and disadvantages. Whilst the chi-squared is widely used it does appear to have a major weakness in that there are no clear guidelines for selecting intervals, leading to discrepancies in the same input data. The K-S does not depend on the number of intervals, which makes it more powerful than the chi-squared test. A weakness of the K-S test is that it does not tail discrepancies very well (Bestfit 1993). The A-D test is similar to the K-S test in that it does not depend on the number of intervals, but it does place more emphasis on the tail values. Even at this stage it is very difficult to select which goodness-of-fit test to use so it is useful to look at what other researchers have used in construction based research. AbouRizk and Shi (1994) have used the K-S test, however, stated that the chi-squared can be reliably used with large data sets (AbouRizk and Halpin 1990). In earlier research, Clemmens and Willenbrock (1978) used the chi-squared test. The A-D test has not been widely used in construction based research. Due to the fact that there is no test that will give you the “best” results it has been decided to use the K-S test in order to avoid the problems associated with class intervals.

On the basis of these results Figure 3 (a, b and c) can be plotted which show the optimum fitted distributions for interarrival, position and pump times. The gamma distribution is used for the interarrival, the exponential distribution for the position time and the less familiar inverse Gaussian distribution is used for the pump time. Bestfit also provides the parameters of these fitted distributions (Table 4.)

**Table 4: Parameters of the probability distributions of best fit.**

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Gamma</th>
<th>Exponential</th>
<th>Inverse Gaussian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>a</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Interarrival time</td>
<td>1.9482</td>
<td>632.17</td>
<td></td>
</tr>
<tr>
<td>Position time</td>
<td></td>
<td>434.95</td>
<td></td>
</tr>
<tr>
<td>Pump time</td>
<td>795.83</td>
<td>1589.5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3a: Fitted gamma distribution to interarrival time of truck mixers

**SIMULATION OF CONCRETE DELIVERY AND PLACEMENT**

Simulation is a well-established technique to analyse models within construction research (see, for example, Tommelien 1997 and Smith 1998). It details the system as it develops over time and its fundamental principle is to reflect the changes of the state of the system as they occur at discrete-events. In this case the events would be either an arrival or a departure of a truck mixer in the system. Only these two events can effectively change the nature of the system that is represented by the state variables. In this model, these are the arrival time of the next arrival, the departure time of the next departure, the state of the placing team and equipment and the number of trucks in the queue. The heart of a simulation is the generation of random variates and in this case three must be considered, the gamma, exponential and inverse Gaussian algorithms to generate the gamma, exponential and inverse Gaussian variates.

There are various ways in which to carry out simulation analysis. For example a dedicated computer program that specifically carries out simulations for a particular model; or alternatively one can use commercial software. In this study the Microsoft Excel add-in @RISK was used. @RISK uses Monte Carlo simulation to carry out “what if” scenarios on specific data and it describes the risk involved with probability distributions.

**Parameters of the Simulation Model**

One of the drawbacks of Monte Carlo sampling is that it creates noise and in order to reduce this the experiment should be repeated many times. Crandall (1997) proved that simulation results would be accurate if a minimum of 1,000 iterations were conducted in the simulation. With this in mind the system was
instructed to carry out 1,500 iterations. It was also decided that 120 events are sufficient in order to represent a typically large concrete pour with 60 arrivals and 60 departures of truck mixers. This represents a pour of approximately 360m$^3$ as the average truck mixer will have a capacity of 6m$^3$ (although this actually exceeds the maximum pour in any one day recorded during data collection.)

Other parameters of the @RISK Monte Carlo simulation model are:

- **Event number** is the number of the event, which can be either an arrival or departure. This is set to 120 events.
- **Event type** identifies the event, whether it is an arrival or a departure of truckmixer.
- **Interarrival time** is the time between successive arrivals of truckmixers on site.
- **Position time** is the time taken by a truckmixer to move from the queue, position at the concrete pump and prepare to discharge the concrete. If no queue is present, it will be the time taken by the truck mixer to position at the pump and prepare for discharging only.
- **Pump time** is the time required for the truckmixer to unload the completely.
- **Time** is the amount of time into the concrete pour.
- **The status** of the concrete pump, where 0 means that the pump is idle and 1 indicates that the pump is busy.
- The number of truckmixers queuing, waiting to be unloaded.
- The time of the next arrival of truckmixer
- The time of the next departure of truckmixer. If the concrete pump is idle, this is set to 9999.
- **Number in system** is the number of truckmixers on site.

**Simulation Results**

There are several operating characteristics that can be considered in concreting operations; four of interest in this study are:

1. The utilisation of the concrete pump,
2. The number of truckmixers in the system,
3. Number of departures, i.e., the number of trucks that have been served, and
4. The total operation time.

These are fundamental to the effective planning of concrete operations and being able to predict these early greatly increase the chance of the operation running smoothly. Table 5 shows the simulation results. The results show the concrete pump is utilised 90.83% of the time from the arrival of the first truck to the departure of the last truck. The average number of truck mixers on site was found to be 4.511. The simulation provided results for 55 departures in a time of 1279 minutes.

**Table 5**: Key characteristics of the simulation model

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Pump Utilisation (%)</th>
<th>Number of Truckmixers</th>
<th>Number of Departures</th>
<th>Total Time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Results</td>
<td>90.83</td>
<td>4.511</td>
<td>55</td>
<td>1279</td>
</tr>
</tbody>
</table>

A sensitivity analysis was carried out in order to find the most significant of the three inputs in the simulation model, i.e. interarrival, position and pump time. The interarrival time was found to be the most significant: by varying the interarrival time the utilisation of the concrete pump can be significantly affected and it will be possible to find the optimum interarrival time.

**Optimum Truckmixer Interarrival Time**

The simulation model can easily be adapted so that it is possible to vary the interarrival time. Instead of using the gamma distribution the interarrival time was replaced with times ranging from 1 to 23 minutes. The operating characteristics can be seen in Table 6.

**Table 6: Varying interarrival times in the simulation model**

<table>
<thead>
<tr>
<th>Interarrival Time (minutes)</th>
<th>Number of Truckmixers</th>
<th>Utilisation of Concrete Pump</th>
<th>Number of Serviced Trucks / 120 events</th>
<th>Total Operation Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56</td>
<td>100</td>
<td>5</td>
<td>114</td>
</tr>
<tr>
<td>3</td>
<td>47</td>
<td>100</td>
<td>14</td>
<td>315</td>
</tr>
<tr>
<td>5</td>
<td>37</td>
<td>100</td>
<td>22</td>
<td>485</td>
</tr>
<tr>
<td>7</td>
<td>31</td>
<td>100</td>
<td>30</td>
<td>623</td>
</tr>
<tr>
<td>10</td>
<td>17</td>
<td>100</td>
<td>43</td>
<td>760</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>100</td>
<td>44</td>
<td>900</td>
</tr>
<tr>
<td>14</td>
<td>13</td>
<td>100</td>
<td>49</td>
<td>980</td>
</tr>
<tr>
<td>16</td>
<td>9</td>
<td>100</td>
<td>53</td>
<td>1066</td>
</tr>
<tr>
<td>17</td>
<td>5</td>
<td>99</td>
<td>56</td>
<td>1071</td>
</tr>
<tr>
<td>18</td>
<td>4</td>
<td>98</td>
<td>56</td>
<td>1137</td>
</tr>
<tr>
<td>19</td>
<td>3</td>
<td>98</td>
<td>58</td>
<td>1159</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>96</td>
<td>59</td>
<td>1200</td>
</tr>
<tr>
<td>21</td>
<td>3</td>
<td>92</td>
<td>59</td>
<td>1260</td>
</tr>
<tr>
<td>22</td>
<td>2</td>
<td>85</td>
<td>58</td>
<td>1320</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
<td>80</td>
<td>60</td>
<td>1378</td>
</tr>
</tbody>
</table>

When choosing the optimum interarrival time several factors have to be considered such as financial viability. It can be seen that having an interarrival time of 1 minute obtains maximum utilisation of the concrete pump - however in order to have such a short interarrival time it is necessary to have 56 trucks on the job. This would not only be very costly but practically impossible. In addition, for the 120 events simulated only 5 of these were departures. Generally, shorter interarrival times result in high utilisation levels of the concrete pump but this is achieved at the expense of many truckmixers being idle on site. An interarrival time of 23 minutes would allow the concrete pour to be carried out by only one truck however the concrete pump utilisation is the lowest of all of the times. This suggests that the truckmixer could have its concrete discharged, travel to the batching plant and uplift the next load and then return to the site within 23 minutes, which would be highly unlikely. The optimum interarrival time from the simulation model would be 19 minutes as this returns a high utilisation level of 98% with an average of only 3 truckmixers present on site.

CONCLUSIONS

Simulation has been shown to be a very useful tool for planners when matching the concrete supply to site requirements. By doing this it should be possible for the contractor to concentrate on bettering performance on site without the worry of the logistics of concrete delivery. Interarrival time of trucks is an essential characteristic of concrete pours and taking this into account at an early stage in a project can greatly increase the utilisation level of the concrete placing equipment and minimise the number of trucks on site. In this study the optimum interarrival time was found to be 19 minutes resulting in a high utilisation of 98% with an average of only 3 truckmixers present on site.

The simulation tool used in this study was the Microsoft Excel add-in @RISK, which was found to be easy to use and should therefore present no problems for contractors to use. It can be easily manipulated to cater for many different pour sizes and operating conditions. It also allows contractors to continually improve the input data by using pours from on-going projects. Finally, simulation allows contractors to investigate the effects of altering the three inputs quickly, without great financial loss and effectively in order to find the optimum operating characteristics for specific concrete pours.

REFERENCES


Abstract
The application of concurrent engineering philosophies to the construction industry follows on from many other manufacturing and production based approaches developed to aid the industry. With increased global competition, the construction industry has realised the need to improve upon its current performances. In order to do this it will be necessary to improve upon the performance of individual processes within a project, which can be assisted by applying concurrent engineering thinking from the design stage of a project and bringing together representatives from every discipline. In this paper the emphasis is placed upon concreting operations, which is one of many activities in a standard construction project. Concurrent engineering ideas are examined and implemented into concreting operations in a bid to improve the overall efficiency of this particular activity within the construction phase of a project's life.

Keywords
Concreting operations, concurrent engineering, construction performance, regression analysis, wasteful activities.

Introduction
The application of concurrent engineering (CE) to the construction industry follows on from many other manufacturing and production based approaches developed to aid the industry. These all have one ultimate aim and that is to make construction ventures more efficient and effective, both financially and on time. However, CE tools introduce a new level of understanding and management techniques that have perhaps been overlooked in the past.

Many researchers have defined concurrent engineering; Dean and Unal (1992) capture the true essence of CE as ‘getting the right people together at the right time to identify and resolve design problems. Concurrent engineering is designing for assembly, availability, cost, customer satisfaction, maintainability, manufacturability, operability, performance, quality, risk, safety, schedule, social acceptability, and all other aspects of the product’.

The above definition of CE at first glance may appear to be perceptible; however, if CE is to make a difference and be embraced by the construction industry all of these factors must be taken into account at the earliest possible opportunity. To achieve this it is necessary to include as many people, from all disciplines, at this early stage. CE advocates that simultaneous consideration of all life-cycle phases using a multi-disciplinary approach must be incorporated (Kusiak, 1993). By doing so effectively a reduction in cycle times, by increasing the degree of integration amongst the activities, can be expected. This will have great benefits on many construction projects as many tend to be engaged in a concurrent environment.

In this paper the project life cycle for a typical civil engineering project shall be considered and an attempt shall be made to examine potential estimating techniques that can be used at early stages in a project's development. If it can be shown that the estimating of concrete operations can be improved at such early stages more informed decisions can be made as to the scope, form and ultimate design of the project. Much of the study will be based on data collected on four major civil engineering projects in the UK, all of which were carried out using traditional methods.

Related background
A large amount of research has taken place within construction processes. Individual activities such as earth-moving operations (e.g. Smith et al, 1995) and concreting operations have been considered. Many tools and techniques have been used to analyse these processes such as simulation models (e.g. Smith, 1998) and the Petri-net theory (e.g. Sawhney et al, 1999), amongst many others.

With the construction industry being subjected to increasing global competition, construction companies are realising that they must become more competitive. This will only become a reality if sufficient attention is given to every activity.

This paper focuses on concrete operations, which can be considered to include, batching, delivery, placement and finally return to the batching plant.

A brief overview of concrete operations
All construction projects involve many separate and individual activities, one of which is the placement of concrete. An increasing number of construction companies are using ready-mixed concrete as an alternative to site mixing. Technical as well as economic considerations influence the choice of alternatives (Lam et al., 1994). The very nature of concrete means that it is very important that delivery times and design specifications are adhered to. Concrete has a 'shelf life' of only a few hours, which makes bulk production impossible, and the planning and scheduling of production and delivery extremely important.

![Figure 1](image-url) A simplified schematic diagram of a typical concrete operation

The concreting process represented here will involve concrete pre-ordered from a batching plant and delivered to a specified site (see figure 1). The batching, delivery and return of truckmixers is termed the 'backcycle'. The arrival, queuing and 'service' process can be considered as a queuing system that will consist of both customers and servers. For each server (concrete pump), customers (truckmixers) 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 back cycle until they rejoin the system — again queuing if the server is busy. The back cycle involves the truckmixers returning to the batching plant and, if required, filling up with concrete.

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 determine the time between arrivals (the interarrival time) of the trucks in order that no queuing, and thus under utilization, of trucks occurred.

Concrete operations in relation to a project’s life cycle
During the early part of the design stage the main form may be known to the designer. Consider figure 2, which is an early sketch for part of a design for a single span concrete bridge. At this stage of design the designer may know what the final bridge will look like but will not know many different construction outputs, such as cost, resources, duration etc. For any concrete element there shall be known inputs which shall influence the outputs (see table 1). The outputs shall not be known at the design stage due to the dynamic nature of many construction projects, however the inputs should be known or at least an assumption can be made regarding them.

Figure 2  Part of a design for a single span concrete bridge
In relation to concurrent engineering philosophies it is at the design stage that much work and effort has to be expended. By increasing the knowledge base at this early stage and by making as many inputs as possible known then models can be developed that help in the approximation of critical outputs. One way of doing this is by early intervention by all disciplines concerned, not only can the inputs be known but also all wasteful activities can be avoided before work has even started on site.

At the design stage, in traditional projects, there are many unknown factors. However, the further along the project life cycle you progress the amount of unknown factors should decrease. This goes to say that by the time the construction phase commences all unknown inputs should be known (figure 3).

**Table 1 Inputs and Outputs for a Typical Project and Status at Design Stage**

<table>
<thead>
<tr>
<th>Design Factors</th>
<th>Status at Design Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of structure</td>
<td>Known</td>
</tr>
<tr>
<td>Shape of structure</td>
<td>Known</td>
</tr>
<tr>
<td>Quality of concrete</td>
<td>Known</td>
</tr>
<tr>
<td>Method of placement</td>
<td>Assumed</td>
</tr>
<tr>
<td>Location of batching plant</td>
<td>Not known</td>
</tr>
<tr>
<td>Amount of reinforcement steel</td>
<td>Known</td>
</tr>
<tr>
<td>Time of year</td>
<td>Assumed</td>
</tr>
<tr>
<td>Site characteristics and layout</td>
<td>Not known</td>
</tr>
<tr>
<td>Production Rate</td>
<td>Not known</td>
</tr>
<tr>
<td>Time</td>
<td>Not known</td>
</tr>
<tr>
<td>Cost</td>
<td>Not known</td>
</tr>
<tr>
<td>Resources Required</td>
<td>Not known</td>
</tr>
</tbody>
</table>

**Design Stage**

- Unknown > 2
- Assumed > 2

**Construction Commences**

- Unknown = 0
- Assumed = 0

**Figure 3 Unknown Input Factors in Relation to the Project Life Cycle**

**Problems related to concrete operations**

Within the construction industry the amount of attention shown to concreting operations has been minimal. Whilst other areas of the industry have been
exploring outside expertise and information technology the concreting side of construction has developed in a piecemeal manner from the early days of construction. At this stage in time, concreting operations are littered with wasteful activities and an attitude that “as long as the concrete arrives everyone is happy” has been adopted on many of the UK’s construction sites.

Tommelein (1999) points out that ‘construction processes are notoriously difficult to plan and control because they are plagued by numerous uncertainties’. These uncertainties ultimately lead to waste within these processes and unless the uncertainties can be identified early on (as in the inputs in table 1) they will lead to many difficulties on site.

Some of these uncertainties, and how determinable they are, can be seen in table 2.

<table>
<thead>
<tr>
<th>Uncertainty Factors</th>
<th>Determinability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Distance between batching plant and site</td>
<td>High</td>
</tr>
<tr>
<td>(2) Road conditions between batching plant and site</td>
<td>Medium</td>
</tr>
<tr>
<td>(3) Traffic levels on road between batching plant and site</td>
<td>Medium</td>
</tr>
<tr>
<td>(4) Site characteristics</td>
<td>Medium</td>
</tr>
<tr>
<td>(5) Access routes on site</td>
<td>Medium</td>
</tr>
<tr>
<td>(6) Weather</td>
<td>Very Low</td>
</tr>
<tr>
<td>(7) Truck-mixer travel speeds</td>
<td>Medium</td>
</tr>
<tr>
<td>(8) Truck-mixer capacity</td>
<td>High</td>
</tr>
<tr>
<td>(9) Truck-mixers available for use</td>
<td>Medium</td>
</tr>
<tr>
<td>(10) Truck-mixer cycle times</td>
<td>Medium</td>
</tr>
<tr>
<td>(11) Pump operator ability</td>
<td>Low</td>
</tr>
<tr>
<td>(12) Pump capacity</td>
<td>High</td>
</tr>
<tr>
<td>(13) Age of pump</td>
<td>High</td>
</tr>
<tr>
<td>(14) Type of pump (mobile or static)</td>
<td>High</td>
</tr>
<tr>
<td>(15) Communication of progress on preceding activities, e.g.</td>
<td>High</td>
</tr>
<tr>
<td>steel work</td>
<td>Medium</td>
</tr>
<tr>
<td>(16) Interarrival time of trucks</td>
<td>Medium</td>
</tr>
<tr>
<td>(17) Idleness of trucks, pump and placing team</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Table 2 Uncertainties in concrete operations

All of the factors in table 2 have been identified due to their ability to lead to waste. The next obvious step is to determine how critical they are to the success of efficient concreting operations. This could be achieved by carrying out a simple regression analysis using records from previous concrete pours.

Regression on actual productivity

For the purpose of this paper data will be used from a civil engineering project involving the construction of a wastewater treatment plant in the northeast of Scotland. The project was carried out using traditional methods and a simple regression analysis was carried out using the data collected. Results of a regression on actual productivity (in volume placed per hour) can be seen in table 3.
The variables used in the analysis have taken into account the inputs identified in table 1, along with others that were identified during the observation of the actual concrete operations.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Notation</th>
<th>Value</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>( T_y )</td>
<td>-1 (summer) or 0 (spring/autumn) or 1 (winter)</td>
<td>4.5718</td>
</tr>
<tr>
<td>Time of year</td>
<td>( V_l )</td>
<td>( m^3 )</td>
<td>0.3396</td>
</tr>
<tr>
<td>Average volume of load</td>
<td>( V_c )</td>
<td>( m^3 )</td>
<td>1.4503</td>
</tr>
<tr>
<td>Total volume of concrete</td>
<td>( N_l )</td>
<td>no.</td>
<td>0.1479</td>
</tr>
<tr>
<td>Number of loads</td>
<td>( N_t )</td>
<td>no.</td>
<td>-0.3438</td>
</tr>
<tr>
<td>Number of truckmixers on job</td>
<td>( T_c )</td>
<td>minutes</td>
<td>0.5937</td>
</tr>
<tr>
<td>Average truckmixer cycle time</td>
<td>( N_w )</td>
<td>-1 (sun), 0 (cloud) or 1 (rain)</td>
<td>-0.0197</td>
</tr>
<tr>
<td>Weather</td>
<td>( N_s )</td>
<td>-1 (base), 0 (wall) or 1 (column)</td>
<td>0.1544</td>
</tr>
<tr>
<td>Shape of structure</td>
<td>( T_s )</td>
<td>1 (6am to 10am), 2 (10am to 2pm) or 3 (2pm to 6pm)</td>
<td>2.0133</td>
</tr>
</tbody>
</table>

Table 3 Results of regression analysis carried out on data from the studied project

Derived model for actual productivity

Finally, it is possible to the linear regression model of actual productivity for concreting operations. This is given by:

\[
P_{\text{actual}} = 0.3396T_y + 1.4503V_l + 0.1479V_c - 0.3438N_l + 0.5937N_t - 0.0197T_c + 0.1544N_w + 2.0133N_s - 0.4381T_s + 4.5718
\]

To demonstrate this model, we can consider an example. If we assume that a concrete operation involves all the characteristics shown in table 4, using the regression model we can estimate actual productivity to be 36.3 m³/hr. This is a realistic value for productivity for such a job.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Assumed Characteristics (value given)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of year</td>
<td>August (-1)</td>
</tr>
<tr>
<td>Average volume of load</td>
<td>6 m³ (6)</td>
</tr>
<tr>
<td>Total volume of concrete</td>
<td>276 m³ (276)</td>
</tr>
<tr>
<td>Number of loads</td>
<td>46 (46)</td>
</tr>
<tr>
<td>Number of truckmixers on job</td>
<td>4 (4)</td>
</tr>
<tr>
<td>Average truckmixer cycle time</td>
<td>72 mins (72)</td>
</tr>
<tr>
<td>Weather</td>
<td>Sunny (-1)</td>
</tr>
<tr>
<td>Shape of structure</td>
<td>Base (-1)</td>
</tr>
<tr>
<td>Start time</td>
<td>0600 (1)</td>
</tr>
</tbody>
</table>

Table 4 Assumed characteristics for example concrete operation
Making use of a regression model at the design stage is an extremely useful tool. Assuming that realistic assumptions can be made at this stage it will aid the designer to better estimate many different outputs such as productivity. If this were not to be used then the designer would have to rely on his or her own experiences and historical data from a different project. This in itself can lead to errors and these will only be noticed during the construction phase and may well add financial burden to the whole project.

Conclusions
This paper has presented tools and techniques for the design and planning of concrete operations. As can be seen, by introducing simple concurrent engineering philosophies to a project at an early stage many savings, both in terms of financial and labour costs, can be made. Concurrent engineering stipulates that at the very earliest possible time individuals from all disciplines should meet and discuss the project in order to overcome any problems and difficulties before construction actually begins.

In the studied project very little or no attempt was made to make use of new philosophies such as the concepts of concurrent engineering. This resulted in wasteful activities such as truck and pump idleness occurring throughout the concreting operations of this project. This inevitably led to a lower productivity than perhaps could have been possible and an increase in the costs of labour and plant hire. This paper also highlighted the benefits of carrying out a regression analysis in order to make predictions of certain outputs.

If concurrent engineering tools had been used in this project, the concrete supplier and contractor would have been familiar with each other's operating strategies. This is extremely important when there is an interface between two or more parties who rely on each other to pass information at different stages to report on the progress of certain activities. An example of this would be if the concrete pump on site unexpectedly broke down, it is extremely important that someone informs the supplier of this so that he can halt deliveries until repairs can be made. Appointing someone in each party to converse with each other when necessary can easily eliminate any possibility of wasteful activities. All of these eventualities must be discussed and certain mitigation measures drawn up at the earliest possible stage of any project.

References


Processes within the construction industry have for many years been systematically modernised and allocated rigid procedures. However, this has not been the case with concrete placing operations. These have been left to evolve naturally and to develop in a piecemeal manner. As a result inefficiencies have become established in concrete operations that have led to wastage in terms of time and money. In a forward-looking industry, in which we are constantly striving to modernise its procedures, it is remarkable that such an area where significant financial savings can be made has been overlooked. There are undoubtedly opportunities for development in this area. Accordingly, this paper considers the amount of wastage involved in the concrete placement process. Results 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 over seventy individual concrete pours. The majority of concrete operations observed involved concrete being pumped into formwork, which was seen to be a complex queuing system. The data collected from actual observations has been analysed using a model that deals with the many factors encountered in concrete placing operations. In this paper the aim is to look, briefly, at queuing systems in general as well as reporting on some of the main findings from the investigation into concrete processes.

Concreting operations, Probability distributions, Queuing systems, Stochastic modelling
INTRODUCTION

For many years now, construction contractors have been using concrete as a construction material. Processes within the construction industry have been systematically modernised and allocated rigid procedures; however, this has not been the case with concrete placing. The process of concrete batching, transport and finally placement is subject to interruption, irregularity and fluctuation for which there can be very little control. Due to their random nature it is possible to treat concrete placement operations as a stochastic system. This random nature suggests that in many cases there is a variable nature to the rate at which material is delivered, which may result in an underutilisation of plant and labour or an additional cost for storage of raw materials. By representing the processes as queuing systems, they can be analysed by a multitude of techniques that are available to the systems analyst, for example queuing theory, regression analysis and simulation. Indisputably it will be advantageous for the industry as a whole to encourage workers to apply management techniques to construction to increase its productivity and effectiveness.

This paper reports on the findings of a pilot study undertaken by the University of Edinburgh in collaboration with Tarmac Civil Engineering (now Carillion plc.). Real construction data were obtained from large concrete pours on a major UK motorway viaduct project, and this provides the basis for the case study in this paper. This paper will look, briefly, at queuing systems in general as well as reporting on some of the main findings from this investigation into concrete processes. This research area is also supported by EPSRC funds: the future development of the project will be discussed.

OBJECTIVES

The main objectives of this work 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 of 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.

STOCHASTIC QUEUING SYSTEMS

In the concreting cycle presented here we will treat it as a single server queuing system (see Figure 1), due to the fact that no account has yet been made of the batching process which can be considered a system in its own right. This means that the only part of the process that must be considered is on site.

The concreting process represented here will involve pre-ordered concrete arriving from a batching plant to site. The queuing system will consist 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 truck mixers arrive they will join the “service” (if there are no other truck mixers in the queue to be served) or join the back of the queue of waiting truck mixers. Service requires the truck mixer 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 truck mixer 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 determine the time between arrivals (the interarrival time) of the trucks in order that no queuing, and thus under utilization, of trucks occurred.

A real system, however, is stochastic and the events that occur within the system will take place at irregular intervals. 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 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.

Although no account, as yet, has been made of the backcycle it is important to appreciate what happens during this time. When the truck mixer is finished discharging the concrete into the hopper it will then have the drum of the mixer washed and then leave the site. After departure the truck mixer will make its way to the designated batcher and then queue again, if necessary, to receive the next batch of concrete.

Identifying uncertainties
When dealing with the concreting system it is important to realise that there are many random factors or uncertainties that will affect its final productivity and effectiveness. The time

variables in question have already been introduced and they are namely truck interarrival, position and pump times. Figure 2 shows how these factors affect the whole system. The factors that affect the time variables are limitless and it will be necessary to identify and manage as many of these as possible. Crombie (1999) calculated as many as 44 factors (see Table 1), both technical and managerial, and although he did not make any suggestions as to how to manage them the findings can be used as a very useful starting point.

![Figure 2. Schematic diagram of the effects that unknown factors have on the concreting placing process](image)

Some of the more obvious factors that may affect the time variables are discussed below.

- **Site location**
  Site location is a very important factor in concrete operations, as the locality of the site will influence the ease at which the concrete can be transported to site, and finally pumped into the required formwork. Time delays can occur if the distance between the batcher and site is too great. It is also important to consider the effects of sites in rural or inner-city locations.

- **Location of Supplier**
  As with site location it is important that in any concreting project a suitable supplier is chosen. The location of the supplier is fundamental to the success of all concreting operations. It must be within a realistic radius of the site – both because the quality of concrete deteriorates with time and also because the delivery cost is proportional to distance. Larger projects will quite often use on-site batchers, which greatly reduce the travel time.

- **Age of Trucks**
  This is an area where no research has, as yet, been carried out. However, it is acknowledged that this could be quite an important factor in the process. Many people within the construction industry feel that the age of trucks may influence the quality of service and concrete being provided; however, this is mostly anecdotal.

- **Site Congestion**
  This may seem an obvious factor but it is one that is not always eliminated. Site congestion can lead to many problems considering the fact that trucks are continually arriving on site and, ideally, should not be held up in anyway.

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

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

As can be seen from Table 1, there are a multitude of factors that affect the process. Probably the most imperative aspect, if the concreting process is to be a success, is that the contractor has a good relationship with the concrete supplier. To a certain extent the contractor is placing great importance on the supplier's integrity. Without a reliable supplier the contractor may be faced with large delays, which will ultimately lead to a poor utilisation of resources. Both contractor and supplier have a vital role to play; firstly, the contractor must order the correct amount and type of concrete for each job and secondly, the supplier must deliver the concrete on time and to the required specifications. This is only one scenario, what must be remembered is that each party will have a large team of workers to manage in order to maximise effort and effectiveness.

Modelling Concreting Operations
As with all modelling exercises, whether physical or numerical, the main aim is to represent the concreting system in a way that can be investigated practically, economically and safely. In modelling the concrete placing process described above, it is necessary to replace the three time components, interarrival, position and pump times, with a probability distribution. It is not necessary to model the queuing time of a truck, as this is a factor of the other time components.

In order to analyse such a system it will be necessary to use techniques available such as queuing theory, simulation, regression analysis, petri-net theory and neural networks. For this paper the data collected has been analysed using discrete-event simulation (for example,

Smith et al. 1996 and Tommelein 1997), where the time components are then represented by probability distributions. These distributions can then be 'sampled' and used to recreate a typical cycle of truck arrival, queue, position and pour. In order that such a system is realistic, it is necessary that it based on actual data from actual site operations; the more real data collected, the more realistic the model becomes.

**Discrete-event simulation modelling**

Full details of the discrete-event model can be found in Smith (1998 and 1999) but to summarise the steps involved are as follows:

- **Data collection.** The model must be based on real data collected from actual construction sites. This is discussed further below.

- **Fitting probability distributions.** The real data is used as the basis for probability distributions – the 'best-fit' distribution is then used in further analysis. This is also discussed below.

- **Generation of random variates.** A random variate is a value generated at random from within the probability distribution chosen. Assuming a good fit between actual distribution and probability distribution the random variate is a true representation of an actual value.

- **Use random variates to synthesise 'events'.** An event is something that changes the state of the concrete placing system. In this case it is either an 'arrival' or a 'departure' of a truckmixer into, or out of, service.

- **Model operations.** A real operation is a series of events, the timing of which determine its attributes (for example, productive output, plant utilisation). These attributes can therefore be determined for a simulated operation.

- **Investigate system.** The real concrete placing system is too large to experiment with but the simulation model of the system can be investigated in many ways.

**Data Collection**

In order to determine the probability distributions that are used to model the concrete placing process, data were gathered from a major civil engineering project in the North West of England. The data gathered were spread over a two-year period, the vast majority of it being collected during the summer months. The project involved the construction of a motorway viaduct and widening and involved pours ranging, for the whole project, from 2m³ to 1200m³ of concrete. A sample of larger concrete pours provided the following data:

- Truck arrival time,
- Pump start time,
- Pump complete time,
- Batching plant used,
- Truck quantity, and
- Concrete slump.

The overall volume of the sampled operations ranged from 33m³ to 470m³ with an average of 180m³. The average number of truckloads was 31 and the average delivery volume was 6.15m³ for the 63 pours sampled.

The data gathered were summarised on a Microsoft Excel spreadsheet and the times of particular interest were extracted. It is necessary to inspect the nature of the distributions of these times prior to fitting any kind of theoretical probability distributions to them. Examples of cumulative distributions of the interarrival, position and pump times can be seen in Figure 3.

![Cumulative distributions of the sampled data](image)

**Figure 3** Cumulative distributions of the sampled data

**Data fitting and analysis**

After determining the observed cumulative distributions (for example as shown in Figure 3), it is then extremely important to represent this observed input data within the model in the form of mathematical probability distributions. It is important that the input data in this form are a good representation of the system – otherwise any output will not be reliable and the model will give ambiguous results.

If the sampled data is to undergo analysis by simulation then it will be important to consider various distributions. From first inspection of the cumulative distributions shown in Figure 3 the normal, uniform, triangular and exponential distributions can be discounted. It is anticipated that it will be preferable to use mathematical distributions such as the beta, gamma and Weibull distributions. The Erlang distribution is another commonly used distribution (for example consider Smith et. al. 1996 and Carmichael 1987), which is a special case of the gamma distribution. It is useful if a good fit is obtained, as it can be quick to generate random variates from.

For the purpose of this paper no comparisons have been made of the different distributions that best fit the data. It is anticipated that this will be possible in the future when more data has been gathered.

CONCLUSIONS

This study has been carried out at a very early stage of the research project and combines early theory with the early stages of data collection and data analysis. Although no 'concrete' results have been found the paper sets about introducing the research topic and some of the methodologies that will be used in the future. From the paper it is possible to show the following conclusions:

1. The study shows that the concrete placing process, common to many thousands of construction sites, may be considered a stochastic system – it can be quite clearly seen from figure 3 that the system is in no way deterministic or non-random. This is a central to the analysis of concreting operations: the random nature of the system's events result in very different characteristics to systems that are considered to be deterministic.

2. The concrete placing operation can be treated as a queuing system, which we encounter in our everyday life, such as at a supermarket or a bank. The queuing system in question will consist of both customers (truck mixers) and servers (concrete pump). From the queuing system it was possible to calculate the length of time each customer spent within the system. The batching process is also a queuing system that, although not considered in this paper, can be treated in a similar manner.

3. Many random factors affect the productivity of the system. These random factors (for example site location, supplier location and site congestion) all have a knock-on effect and affected the time variables – truck interarrival time (time between arrivals), truck position time (the time it takes a truck to move into position so that it is ready to discharge it's load into the pump hopper) and the pump time (the time taken to pump the concrete into the formwork). This will inevitably cause a certain degree of time delays within the system that will result in wastage, both in financial and human contexts.

4. It is possible to analyse such systems using a variety of techniques such as regression analysis, simulation, queuing theory, petri-net theory and neural networks.

5. Data from a large civil engineering project was used as a pilot study at the beginning of the research. From the data collected it was possible to calculate the three most relevant times and the average number of truckloads, which was found to be 31. The average delivery volume was found to be 6.15m$^3$ for the 63 pours sampled. The cumulative distribution of the raw sample data was calculated and this is what would form the basis of the model analysis. It was concluded that the four most obvious distributions to consider are the beta, gamma, Erlang and Weibull distributions.

FURTHER WORK

This area of study has a large potential for future research; it is intended that the following directions will be pursued:

- To take forward the initial studies and apply the data collected to probability distributions.

• The initial studies only used data from one site collected in the summer months. It is anticipated that further studies can be conducted using multiple sites, with varying conditions (such as type of pour and 'urban' or 'rural' for example) and data collected at different times in the year.
• Investigations shall take place into effects of different contractors and concrete suppliers. As mentioned in the paper the relationship between the two parties is critical so it will be necessary to investigate how each rely and support each other.
• As mentioned in the paper, the model used simplifies the actual process by ignoring the batching stage and backcycle so it may be necessary to take these into account in the future.
• As discussed there are limitless numbers of factors which affect the system so further work will have to be carried out to identify many more of these uncertainties.
• In ideal situations, all of the concrete delivered to site would meet all necessary requirements but unfortunately this is not the case. Every batch of concrete's slump is tested and unless this is within the set limits it is rejected. This delays the process and has a knock on effect further down the line. Studies will be carried out to determine the effects this has on the process as a whole.

REFERENCES

A NON-DETERMINISTIC INVESTIGATION OF THE CONCRETE PLACING SYSTEM

Paul Dunlop, Simon Smith

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

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 PHILOSOPHY 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](image)

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)

<table>
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<tr>
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<th>MANAGERIAL FACTORS</th>
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<tbody>
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<td>22. PLANNING</td>
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<td>18. CONCRETE SPECIFICATIONS</td>
<td>39. QUALITY OF PLANT</td>
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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 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](image-url)  
*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 be 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*

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 276m³ of concrete. Figure 3 shows the result of this experiment.

![Figure 3: Results of an experiment in varying the interarrival time](image)

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.

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 is 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


ABSTRACT: Processes within the construction industry have for many years been systematically modernised and allocated rigid procedures. However, this has not been the case with concrete placing operations. These have been left to evolve naturally and to develop in a piecemeal manner. As a result inefficiencies have become established in concrete operations that have led to wastage in terms of time and money. In a forward-looking industry, in which we are constantly striving to modernise its procedures, it is remarkable that such an area where significant financial savings can be made has been overlooked. There are undoubtedly opportunities for development in this area. Accordingly, this paper considers the amount of wastage involved in the concrete placement process. Results 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 over seventy individual concrete pours. The majority of concrete operations observed involved concrete being pumped into formwork, which was seen to be a complex queuing system. The data collected from actual observations has been analysed using a model that deals with the many factors encountered in concrete placing operations. In this paper the aim is to look, briefly, at queuing systems in general as well as reporting on some of the main findings from the investigation into concrete processes.

Keywords: Concreting, Stochastic Systems, Probability Distribution, Queuing Systems

1. INTRODUCTION

For thousands of years, concrete has been used as a construction material. However, as processes within the construction industry have been systematically modernised and allocated rigid procedures, this has not been the case with concrete placing. The process of concrete batching, transport and finally placement is subject to interruption, irregularity and fluctuation for which there can be very little control. Due to their random nature it is possible to treat concrete placing operations as a stochastic system. This random nature suggests that in many cases there is a variable nature to the rate at which material is delivered, which may result in an underutilisation of plant and labour or an additional cost for storage of raw
materials. By representing the processes as queuing systems, they can be analysed by a multitude of techniques that are available to the systems analyst, for example queuing theory, regression analysis and simulation. Indisputably it will be advantageous for the industry as a whole to encourage workers to apply management techniques to construction to increase its productivity and effectiveness.

This paper reports on the findings of a pilot study undertaken by the University of Edinburgh in collaboration with Tarmac Civil Engineering (now Carillion plc.). Real construction data were obtained from large concrete pours on a major UK motorway viaduct project, and this provides the basis for the case study in this paper. This paper will look, briefly, at queuing systems in general as well as reporting on some of the main findings from this investigation into concrete processes. This research area is also supported by EPSRC funds: the future development of the project will be discussed.

2. OBJECTIVES

The main objectives of this work were:

- 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 of 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.

3. MODELLING THE CONCRETE PLACEMENT CYCLE

3.1 Queueing Systems

As with all modelling exercises, whether physical or numerical, the main aim is to represent the concreting system in a way that can be investigated practically, economically and safely. In the concreting cycle presented here we will treat it as a single server queuing system (see Fig. 1). No account has yet been made of the batching process as it can be considered a system in its own right and may be considered in future work.
Figure 1. Schematic diagram of a general Concrete Placing Cycle.

A queueing system consists of both customers and servers, Carmichael (1987). For each server, customers will queue until they are served and then leave. In the case of the Concrete Placing Cycle (CPC) 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 many of the 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 queueing 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 determine the time between arrivals (the interarrival time) of the trucks in order that no queueing, and thus underutilization, of trucks occurred.

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).

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 Cycle. Queueing 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 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.

As can be seen, the output of the system is dependent on the variability of the system events. What must also be considered are the factors that influence this variability.

3.2 Factors affecting the CPC

In the majority of concrete pours it is possible to determine a number of factors that affect the effectiveness and efficiency of the Concrete Placing Cycle. Establishing these factors may well improve the efficiency 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 practise. Crombie concluded that as many as 44 factors would need to be managed, as best as possible, in order to achieve a satisfactory output.

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

<table>
<thead>
<tr>
<th>TECHNICAL FACTORS</th>
<th>MANAGERIAL FACTORS</th>
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<tbody>
<tr>
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<td>43. ACCIDENTS</td>
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<td>44. WEATHER CONDITIONS</td>
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Although Table 1 deals with 44 factors some of these are inter-related and some have a very low probability of occurring. These factors all influence the time components previously mentioned. These components will be discussed in more detail later on. Some of the more important factors from Table 1 are discussed below.

- **Site location**
  Site location is a very important factor in concrete operations, as the locality of the site will influence the ease at which the concrete can be transported to site. Time delays can occur if the distance between the batcher and site is too great. It is also important to consider the effects of sites in rural or inner-city locations.

- **Location of Supplier**
  As with site location it is important that in any concreting project a suitable supplier is chosen. The location of the supplier is fundamental to the success of the concreting operation. He must be within a realistic radius of the site as the quality of concrete deteriorates with time. More and more contractors are using on-site batchers, which greatly reduce the travel time.

- **Age of Trucks**
  This is an area were no research has, as yet, been carried out, however, it is felt that this could be quite an important factor in the process. Many people within the construction industry feel that the age of trucks may influence the quality of service being provided, however this is mostly anecdotal.

- **Site Congestion**
  This may seem an obvious factor but it is one that is not always eliminated. Site congestion can lead to many problems considering the fact that trucks are continually arriving on site and cannot be held up in anyway.

### 3.3 Stochastic Model and Analysis

In modelling the random Concrete Placing Cycle as described above, it is necessary to replace certain time components with a probability distribution. If the assumption is made that trucks randomly arrive at site and are not considered once they leave there are only three times which have to be evaluated: interarrival time, truck positioning time (at the pump) and concrete pumping time. It is possible to investigate the concrete system by using discrete-event simulation, Smith (1998,1999). When analysing the cycle by simulation, times from these distributions can then be “sampled” and used to recreate a typical cycle of truck arrival, queue, position and pour. The simulation of multiple cycles can then provide attributes of a particular operative set-up, such as overall time, average pump rate or plant utilization rates. In order that such models are realistic, it is necessary that they be based upon actual data from actual site operations.

4. PILOT STUDY

4.1 Data Collection

It is fundamental that for models to be a good representation of real life projects they must be based on real data. In this pilot study data were gathered from a major civil engineering project in the North-West of England. The data gathered was spread over a two-year period, however the vast majority of data was collected during the summer months. 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. A sample of larger concrete pours provided the following data:

- Truck arrival time,
- Pump start time,
- Pump complete time,
- Batching plant used,
- Truck quantity, and
- Concrete slump.

The overall volume of the sampled operations ranged from 33m$^3$ to 470m$^3$ with an average of 180m$^3$. The average number of truckloads was 31 and the average delivery volume was 6.15m$^3$ for the 63 pours sampled.

The data collected were summarised on a Microsoft Excel spreadsheet and the times of interest extracted. The nature of the distribution of these times can be inspected and Figure 2 shows the cumulative distribution of the interarrival, position and pump times.

4.2 Probability Distributions

The data gathered from the observed project can provide us with certain statistics of the three principal time factors that have been mentioned previously. Table 2 shows that the variability of the observed data is extensive. Although averages can be computed, the use of these in a model would not represent the cycle realistically and one could not assume that the model is valid. It is therefore necessary to be able to recreate the variability. The easiest way is to use the sample directly from the raw, observed data in a random manner. Such a model would have drawbacks in that it can only reproduce historical events and then only with what may be a limited amount of data. It is advantageous to be able to represent the variability through probability distributions.

The use of probability distributions in modelling stochastic systems is extensive. Examples are given in many references (for example Smith et al (1996) and Carmichael (1986)) and the modeller generally has two approaches: to use the observed data to define an empirical distribution or to 'fit' a theoretical distribution to the observed data. The second approach is preferable as it allows the modeller to analyse the system for situations outside what may be deemed normal. In the pilot study the beta, gamma and Weibull distributions were considered.

Table 2. Summary of data gathered from pilot study.

<table>
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<tr>
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<th>Intarrival time/s</th>
<th>Position time/s</th>
<th>Pump time/s</th>
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<td>1858</td>
<td>1634</td>
<td>1839</td>
</tr>
</tbody>
</table>

5. DISCUSSION AND CONCLUSIONS

This paper has shown that the delivery of concrete, to a construction site, is a complex system that can benefit from better planning.

- The study has verified that the Concrete Placing Cycle can be considered to be a stochastic system. It is essential that this is appreciated as, due to the random nature of their events, such systems display performance features somewhat different from those that may be determined if the system is considered non-random.

- By understanding the Concrete Placing Cycle it can be seen that it may be treated as a queuing system, which we are confronted with in our everyday lives. Within the queuing system there are many factors, both technical and managerial, that can affect the quality of the process.

- The case study presented in this paper used data from a major civil engineering road-widening project. From the data it was seen that three time factors made up the concrete model: truck interarrival time (time between arrivals), truck position time (the time it takes a truck to move into position so that it is ready to discharge it's load into the pump hopper) and the pump time (the time taken to pump the concrete into the formwork).

- It is possible to represent the variability of the sampled data through probability distributions.

6. FUTURE WORK

It is believed that this area of study has potential for future research and it is intended that it will pursue the following directions:

1. To take forward the initial studies and apply the data collected to probability distributions.

2. The initial studies only used data from one site collected in the summer months, it is hoped that further studies can be conducted using multiple sites and data collected at different times in the year.

3. Investigations shall take place into effects of different contractors and concrete suppliers.

4. As mentioned in the paper, the model used simplifies the actual process by ignoring the batching stage and backcycle so it may be necessary to take these into account in the future.

5. It may be useful to look at different site locations, comparing for example, rural sites to inner-city sites.

6. The age of the trucks being used is believed by many to be an important factor in the cycle so this will be investigated further.

7. Although in this paper the Concrete Placing Cycle was analysed using queuing theory, investigations are going to be undertaken to establish the possibility of using other methods, such as, nonsequential processes like petri-net theory.

8. In ideal situations, all of the concrete delivered to site would meet all necessary requirements but unfortunately this is not the case. Every batch of concrete’s slump is tested and unless this is within the set limits it is rejected. This delays the process and has a knock on effect further down the line. Studies will be carried out to determine the effects this has on the process as a whole.

7. REFERENCES


STOCHASTIC MODELLING OF CONCRETE OPERATIONS

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The concrete delivery and pumping process is a stochastic system. If analysed deterministically there is the danger that the negative effects of the random distribution of events are not taken into account, leading to poor estimates of production and cost. By representing the system as a random process the construction engineer can firstly achieve improved estimates of the overall productivity and thus schedule deliveries better, and secondly, determine the effect of non-anticipated events such as excessive delivery or pour times. Research will be centred on studies of actual construction projects, which will be used to study cyclic processes in general, and concreting placing operations in particular. In addition, data will be gathered from concreting operations, which will be used as a basis for the modelling of concreting operations. These models will be developed and analysed using a number of techniques, notably discrete-event simulation, with the intention of producing software for the practical analysis of site operations. The ultimate aim of the investigation is to minimise the cost and maximise the productivity of concreting operations.

Concreting, Modelling, Queuing Systems, Stochastic Systems

INTRODUCTION

For thousands of years, concrete has been used as a construction material. However, as processes within the construction industry have been systematically modernised and allocated rigid procedures, this has not been the case with concrete placing. The process of concrete batching, transport and finally placement is subject to interruption, irregularity and fluctuation for which there can be very little control. Due to their random nature it is possible to treat concrete placement operations as a stochastic system. This random nature suggests that in

many cases there is a variable nature to the rate at which material is delivered, which may result in an under utilisation of plant and labour or an additional cost for storage of raw materials. By representing the processes as queuing systems, they can be analysed by a multitude of techniques that are available to the systems analyst, for example queuing theory, regression analysis and simulation. Indisputably it will be advantageous for the industry as a whole to encourage workers to apply management techniques to construction to increase its productivity and effectiveness.

This paper reports on the findings of a pilot study undertaken by the University of Edinburgh in collaboration with Tarmac Civil Engineering (now Carillion plc.). Real construction data were obtained from large concrete pours on a major UK motorway viaduct project, and this provides the basis for the case study in this paper. This paper will look, briefly, at queuing systems in general as well as discussing the proposed research methodology.

OBJECTIVES

The main objective of this work is:

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

METHODOLOGY

There are two main aspects to the project; firstly, it is important to find suitable live construction sites for further study. These sites should initially allow observation of concrete operations to provide a full understanding of the procedures and activities that make them up. The factors that influence their output and the differences between contractors, geographical areas, time of year and weather. Concreting operations will also be observed on a work-study basis in order to extract raw data that can be later used as model input. Secondly, it is

anticipated that it will be possible to develop numerical models of the concreting process and analyse these in a variety of ways. Discrete-event simulation has, to date, already been implemented on earthmoving processes as well as concreting processes by Smith (1998,1999). It is hoped that this technique may be used again using both commercially available software and new applications developed for this purpose by the author; other methods will also be investigated, for example queuing theory, regression analysis and the petri-net theory.

The analysed models will be used in two ways: firstly, to undertake parametric experiments on the concreting process, and secondly to provide a tool for the estimation, planning and management of concreting operations.

The research project should follow a pre-determined plan if it is to run both effectively and efficiently. However research is a dynamic process, therefore there must be a certain amount of flexibility – implying, although not requiring, that a contingency approach would be helpful.

The research project is expected to follow the following route.

1. Literature Survey

An essential early stage of virtually all research is to search for and to examine potential relevant theory and literature. Theory and literature are the result of previous research projects.

For this particular project the literature survey has almost been completed, however, it is fair to say that it may never be entirely finished. The survey took advantage of the multitude of powerful search engines available on the World Wide Web and these yielded many favourable results. The majority of research found relating to concrete operations took place outside of the UK so from a very early stage it was noted that there was definite research potential within the UK.

2. Model Development

As with all modelling exercises, whether physical or numerical, the main aim is to represent the concreting system in a way that can be investigated practically, economically, and safely. In the concreting cycle presented here we will treat it as a single server queuing system (see Fig. 1). No account has to date been made of the batching process as it can be considered a system in its own right and may be considered in future work.

A queuing system consists of both customers and servers, Carmichael (1987). For each server, customers will queue until they are served and then leave. In the case of the Concrete Placing Cycle (CPC) 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 many of the 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 determine the time between arrivals (the interarrival time) of the trucks in order that no queuing, and thus underutilization, of trucks occurred.

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).

A real system 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 Cycle. 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 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.

As can be seen, the output of the system is dependent on the variability of the system events. What must also be considered are the factors that influence this variability. In the majority of

concrete pours it is possible to determine a number of factors that affect the effectiveness and efficiency of the Concrete Placing Cycle, such as site location, location of the supplier and the age of trucks. Establishing all of these factors may well improve the efficiency of concrete operations and so reduce wastage.

3. Data Collection

It is fundamental that for models to be a good representation of real life projects they must be based on real data. In this pilot study data were gathered from a major civil engineering project in the North-West of England. The data gathered was spread over a two-year period, however the vast majority of data was collected during the summer months. The project involved the construction of a motorway viaduct and widening and involved pours ranging, for the whole project, from 2m³ to 1200m³ of concrete. A sample of larger concrete pours provided the following data:

i. Truck arrival time,
ii. Pump start time,
iii. Pump complete time,
iv. Batching plant used,
v. Truck quantity, and
vi. Concrete slump.

The overall volume of the sampled operations ranged from 33m³ to 470m³ with an average of 180m³. The average number of truckloads was 31 and the average delivery volume was 6.15m³ for the 63 pours sampled.

Table 1 shows a typical example of a data sheet that provided the basis for the investigation. The data collected were summarised on a Microsoft Excel spreadsheet and the times of interest extracted.

Table 1 A typical example of a data sheet used on site to record relevant times.

<table>
<thead>
<tr>
<th>Pour Date</th>
<th>Location</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Interarrival Time</th>
<th>Truck Wait Time</th>
<th>Truck Position Time</th>
<th>Load Pump Time</th>
<th>Pump Time</th>
<th>Operation Inactive Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch Arrive</td>
<td>Start Complete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As mentioned previously, the pilot study only considered data from 63 pours. It is intended that further sites will be selected to enable a wider range of data to be sampled. Due to the wide variety of construction sites, data will be gathered from very different site locations, for example the comparisons between rural and inner-city sites.

4. Data Analysis

Analysis may be carried out with respect to data available, the objectives and any hypothesis, so that the most robust and rigorous analytic methods will be used, thereby maximising confidence in the results (Fellows et al, 1999). It is important to consider, evaluate and plan analysis methods from the very beginning.

Analysis can begin by examining the raw data, gathered from construction sites, for patterns and relationships. It was hypothesised at the start of the literature survey that the most relevant times from the concreting system were the interarrival, position and pump times. These can now be subjected to statistical analysis and it is normal to analyse queuing systems in a non-deterministic way using methods that will be discussed below.

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. Simulation involves the use a model to represent the essential characteristics of a reality, either a system or a process. So, whilst a model may be a static representation, such as an architectural model, a simulation 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.

iii. Petri Net Theory. Petri nets are used as a tool for the study of systems. Petri net theory allows a system to be modelled by a Petri net, a mathematical representation of the system. 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.

5. Further Data Collection

After the initial data has been gathered and analysed it will be necessary to collect further data. This will involve going to different sites in order to get a wider range of data for sampling and to put right any errors which are felt may be in question from the first data collection. The process of going back on to site multiple times allows for any new ideas and thoughts to be explored.

6. Model Verification

After the model or models have been researched and put in place it is important to refine them to ensure that they are being used to their full capacity. Verification of a model involves determining whether the structure of the model is correct; this is achieved by testing the model, by examining the outputs resulting from the model under a given set of inputs. The

model is verified if the outputs are appropriate, i.e. they approximate to ideas of what a good model would generate.

7. Validation

The next stage of any modelling process is validation. At this point any model that was not verified must be discarded or undergo further amendments. The validation of a model is fundamental to the achievement of one's initial aims and objectives. If the model is not an accurate representation of the system being studied then any conclusions gained from the model cannot be relied upon. When carrying out the validation stage it will be useful to test several sets of input data and known outputs over a range of conditions — including extremes. When more than one model is being used and has passed verification then it will be necessary to choose the most appropriate model.

8. Dissemination

When the final model has been chosen it is going to be important to disseminate the results and findings appropriately. This is an integral part of any research project. It is hoped that the results of the project will show that there are definite signs of ways to minimise the cost and maximise the productivity of concreting operations.

BENEFICIARIES

Potential impact of the work

The results of this work will have the potential to:

i. Assist in the planning and estimation of concrete placing operations. Construction contractors normally have a very short period of time in which to do this when tendering and thus increased accuracy and speed would be welcome.

ii. Assist in the management of concrete placing operations. Operations on a construction site may often be conducted in a reactive way, responding to events as they happen. By increasing the understanding of planned operations, site personnel may be better placed to manage them pro-actively.

iii. Increase efficiencies, reduce wastage and increase cost effectiveness of concrete placing operations. Smith (1998) has already indicated that cost reduction of concreting operations is a possibility through a stochastic as opposed to a deterministic approach.

iv. Provide a base of experimentation and results for other internationally.

Beneficiaries of the research project

The beneficiaries of this work are primarily expected to be construction organisations, from the increased competitiveness through the minimisation of cost and maximisation of productivity. Particular beneficiaries within the construction industry will be:

i. Contractors, who will benefit from improved planning and increased productivity; and
ii. Materials suppliers, who will benefit from reduced costs through increased utilisation of equipment.

It is expected that the academic community of workers in process modelling will also benefit.

REFERENCES


