ANGLIA RUSKIN UNIVERSITY

FACULTY OF SCIENCE AND ENGINEERING

A NOVEL DATA-DRIVEN TOOL TO IMPROVE CONSTRUCTION SCHEDULE ACCURACY

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ANGLIA RUSKIN UNIVERSITY

ABSTRACT

FACULTY OF SCIENCE AND TECHNOLOGY

PROFESSIONAL DOCTORATE

A NOVEL DATA-DRIVEN TOOL TO IMPROVE CONSTRUCTION SCHEDULE ACCURACY

Barry Talbot

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Construction schedules are frequently criticised for inaccuracy and poor project performance, including unplanned and preventable costs and delays. Currently, project planning involves the use of rules of thumb and memories of the outcome of previous similar tasks, leading to optimism bias where the predicted duration is shorter than the actual duration. Reinforced concrete (RC) frames are recognised as critical components of tall buildings, with the gap in practice identified as the inaccurate scheduling of RC frame structures. This research aims to produce a novel tool to enhance construction project management by improving construction schedule accuracy in reinforced concrete (RC) frame buildings, with current scheduling practices and site productivity investigated and the tool developed and validated.

A questionnaire survey was undertaken to investigate the phenomenon of inaccurate scheduling found in practice, followed by a series of seven interviews to further probe the results of the questionnaire. Six recently completed projects were then examined to determine discrepancies between the predicted and achieved schedule durations. The findings of the data collection were analysed quantitatively, with the duration to install formwork and reinforcement determined to be the most critical tasks to schedule accuracy in RC frame structures.

A tool (Calchas) was then created to predict future task durations by collecting and analysing productivity-related data to identify the most likely task duration using reference class forecasting. A novel algorithm was developed to collect and store project performance metrics, where the data is interpreted by a sequence of code and stored in a structured, searchable planning knowledge database. A second novel algorithm was then created with associated code developed to extract relevant data from the database and forecast task durations with a view to increasing the accuracy of the construction schedule and enhancing the planning decisions made.

Keywords:

Planning, Project Management, Reference Class Forecasting, RC Frame.

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Definitions

Carpenter: A carpenter is a tradesperson whom erects formwork.

Code: Code, or source code is the text written by humans to interact with computers, such as Visual Basic, C#, Java or Python.

Coding: Coding is the process of writing code.

Data: In terms of progress, data refers to the raw metrics collected from site, such as number of days, tonnes of reinforcement or square metres of formwork. Data must be interpreted to convert it into information.

Decking, deck: Horizontal formwork, used in the construction of concrete floors.

Effort: The effort is the amount of work hours required to complete a task. For example, formwork effort is measured in carpenter-days or carpenter-hours, with reinforcement effort expressed in steel fixer-hours or steel fixer-days.

Fixer: See *steel fixer*

Formwork: A mould and supporting structure which accepts fluid concrete.

MAD: Mean Absolute Deviation, a measure of the distribution of data points relative to each other, indicating spread.

Pour, pouring: An area of concrete to be cast, such as a slab pour; The process of placing fresh fluid concrete

Production rates: Linked to productivity, the production rate is the rate at which work is produced.

Productivity: Productivity is the quantity of goods and services a worker produces in a given amount of time. For example, the productivity of carpenters can be measured in m^2 of formwork erected per carpenter per day.

Programme: the term *programme* has many meanings; in the context of this research, it is a collection of projects.

Progress: Progress is the amount of work done between two points in time. For example, the progress for a week is the difference in work done between the beginning and the end of the week.

RC: Reinforced concrete, the construction material which consists of concrete with embedded metal giving increased strength.

RCF: Reference Class Forecasting is a method which uses data collected from similar past events to predict the outcome of future events.

Reinforcement: Steel bars embedded in concrete providing strength.

Schedule: A schedule is created by a planner or project manager as a roadmap to construct a project, usually in the form of a Gantt chart.

Steel fixer, Fixer: A steel fixer is a tradesperson that places reinforcement into or on formwork prior to the placement of fresh, fluid concrete.

Striking: The removal of formwork when concrete has reached sufficient strength to support its own mass.

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1 Introduction

Significant criticism has been levelled at the construction industry by a number of influential reports highlighting its poor performance, including late project delivery and excessive costs. The construction industry has been described during the Rethinking Construction campaign in the UK as ‘adversarial’, ‘ineffective’ and ‘incapable of delivering for its customers’ (Latham, 1994), whilst Egan (1998) stated that ‘the industry as a whole is underachieving’. More recently, construction has been held to task for the routine acceptance of poor performance (Farmer, 2016). It would appear that the same problems prevail today, indicating the slow pace of change over the last 25 years, a symptom of what Farmer (2016) calls ‘a deep-seated cultural resistance to change pervading [in the industry]’.

These continuous criticisms are noteworthy as the construction industry is a substantial component of the UK economy, accounting for up to 15% of GDP (Asadi, et al., 2020), and employs almost 7% of the UK workforce (Rhodes, 2019). More concerning are the statistics relating to project delay, where, in the UK in 2018, only 59% of construction projects were completed on time (Glenigan, 2019), although only 33% of high-rise projects are delivered on schedule (CIOB, 2008), the majority of which are reinforced concrete (RC) frame buildings. It is clear from these statistics, and from first-hand industry experience, that high-rise projects involving RC frames have a significant likelihood of being delivered late. Underlining the criticality of RC frames, research undertaken by Pellegrino *et al.* (2012) found that concrete structures are crucial to project cost and duration:

> ‘…a concrete structure represents up to 30% of the total cost of construction of a building, and it is always on the critical path. Thus, any improvement in its planning and execution has a significant impact on the overall performance of a project.’

1.1 Planning in Construction

Effective planning is critical to reducing construction waste and the achievement of profitability and customer satisfaction (Li, 2008) and due to its complexity, has become an intricate task demanding collaboration from a diverse set of temporal team members (Anumba, et al., 2000). One significant impediment to planners developing project plans is the necessity to make assumptions and estimates of how the project will unfold, in an iterative process which is repeated until a satisfactory project solution is achieved, a challenge which is becoming intensified by increasingly complex buildings, components and contractual mechanisms (Li, 2008). Despite the criticality of correct planning, construction planners tend to be overwhelmed with information of poor quality. Winch and Kelsey (2005) conducted interviews with 18 construction planners in the UK and found that the uncertainty caused by design deficiencies were dealt with in a number of ways, including:

- Using experience and past job records to guess the missing information
- Submitting a tender bid with qualifications and exclusions
- Adjusting the risk premium according to their assessment of risk presented by the missing information.
- Relying on recovering time and money through a rigorous contractual stance on site, pursuing variation orders and requests for change through the duration of the project

A further difficulty with achieving project planning success is the fundamental requirement to satisfy the demands of the iron triangle of time, cost-effectiveness and quality (Alshamsi, 2019), with the effective delivery of construction projects acknowledged by Hughes (2020) as a comprehensive process lying at the centre of the infrastructure and urban development industry. It was found that successful project execution is dependent on engaging staff with the right knowledge, skills and abilities to plan and undertake the project (Hughes, 2020).

1.2 Gap in Practice

The reasons for delay have been the subject of both commercial investigation and academic research and, whilst there is no conclusive evidence identifying why delays persistently occur, a prominent reason has been found to lie with the project planning process, where the project schedule has not been compiled correctly. Planning in construction involves, amongst other things, the compilation of construction schedules to enable project managers to control the sequence and duration of the works. Studies into the performance of projects against their estimates (Flyvbjerg & COWI, 2004; Flyvbjerg, 2014; Flyvbjerg, 2016; Cunningham, 2017; Budzier, et al., 2018) have shown that actual project duration is consistently and systematically longer than predicted. One area of research is the mental process of planning, with one solution to overcoming errors promoted by Weise *et al.* (2016). Here, it was found that 'backward planning' tasks from completion to commencement caused planners to think more critically about the series of tasks required and consequently overcome bias. However, this approach does not assist in predicting the duration of tasks, rather it helps in structuring the detail of the task. Holding a different view, Flyvbjerg (2014) builds on the Nobel Prize-winning work of Kahneman and Tversky

(1979) relating to optimism bias, proposing that it is the prime root cause of schedule and cost overrun in construction, opining that projects themselves are not necessarily failures, but the failure lies squarely with the planner. The gap in practice is therefore identified as how to schedule correctly, which is manifested as discrepancies between the predicted and actual durations for their construction.

1.3 Research Focus

1.3.1 Research Aim

The aim of this thesis is to produce a novel tool to enhance construction project management by improving construction schedule accuracy in reinforced concrete (RC) frame buildings.

1.3.2 Research Objectives

The research problem relates to the production of inaccurate schedules, where planned task durations should reflect actual durations, but in practice they do not. In response, this research focuses on the development of a process to improve construction schedule forecasting in reinforced concrete frames using historic performance data. To develop this concept, the research problem has been decomposed into four Research Objectives as shown in Table 1-1 below.

Table 1-1. Research Objectives

Research Objectives	
RO1	To understand the state-of-the-art of scheduling practices in the UK.
RO2	To critically review the current scheduling practices in the UK.
RO3	To investigate construction site productivity
RO4	To develop and validate a tool to improve construction schedule accuracy

1.3.3 Central Question

The central research question is identified as how the creation of inaccurate construction schedules can be overcome.

1.3.4 Outline Methodology

This study adopts a data-driven mixed-methods approach mainly using quantitative data, reflecting the researcher's objectivist perspective that 'the truth is out there'. The methodological approach has been chosen as post-positivism, using questionnaires and interviews to collect initial data. Unobtrusive research is carried out on historic construction schedules and associated project documents to gather project data. The collected data are analysed statistically and the results used to develop a system to analyse project performance with a view to predicting future task durations.

There are discrepancies frequently encountered in the duration of planned and achieved progress in construction projects, with industry experience suggesting that inaccuracies in the tender estimates of time on project schedules can lead to project failure. The inaccuracies are rooted, according to academics, in bias and the planning fallacy, where planners estimate that tasks will take less time than they actually require (Sample, 2015; Flyvbjerg, et al., 2018). This implies that it would be beneficial to find a quantified or analytical method to determine, based on accurate historic project performance, a more precise method for estimating project durations. Aligned with the view of Pellegrino *et al.* (2012), this research holds that correct planning and control of site work activities is a prerequisite for the successful execution of a construction project with the intention of improving the ineffective planning currently practiced, as found by both academic literature and as experienced in industry. To achieve this position, it is proposed to create a knowledge database of measured on-site performance and the development of an interface enabling secondary users to interact with the database and extract task duration predictions, based on a statistical analysis of past performance.

The research outline model in Figure 1-1 maps out this research, where current planning assumptions are informed by a literature review and the current state of the art in planning, permitting the formulation of a database structure.

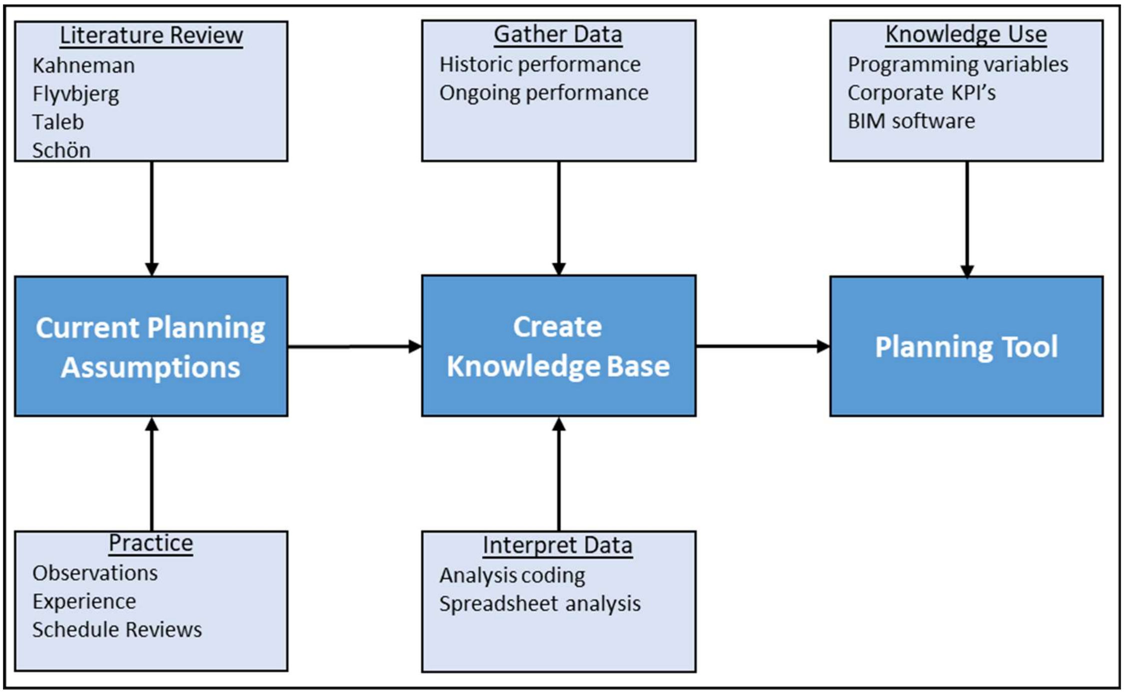


Figure 1-1 Research Outline Model

A company-wide database of planning knowledge may be created by gathering data from historic and ongoing project performance, allowing the user to enter salient weekly productivity data when the project enters the construction stage. The schedule assumptions and decisions may be interrogated and verified by measuring and recording productivity in the database. The data can then be interpreted and analysed by a software algorithm which automatically structures the data and enters it in the knowledge database. Each successive addition of data to the knowledge database enhances the accuracy of the statistical analysis, where the coding could indicate the expected duration for the formwork and reinforcement installation tasks, based on the geometric properties of the element under consideration and the recorded historic performance of the work force.

Performance and production rates are crucial as they are used at contract tender stage to inform budget estimates and influence construction schedules, and any inaccuracies can lead to costly over- or under-estimation of time and cost. It is considered that more accurate measurement and reporting of project performance could provide a number of benefits, including:

- Increased commercial certainty
- Enhanced corporate reputation
- Increased trust between project stakeholders through increased accuracy in schedule delivery
- Improving the image of construction by providing accurate schedules of work

Achieving these outcomes will realise greater efficiencies, leading to increased commercial advantage. Effective performance measurement can also support the improvement of overall construction performance (Hu & Liu, 2016). Pellegrino *et al.* (2012) also promote the measurement of productivity, pointing out that, in addition to gaining knowledge benefit, there are other reasons to undertake rigorous planning of construction projects, including contractual compensation clauses, the timing of progressive payments and the threat of liquidated damages. These penalties and enticements induce, according to the authors, contractors to undertake careful planning and control of the resources, including labour, equipment and materials, where determining the expected productivity for construction activities is the basis for achieving a realistic time schedule. The productivity of a task is generally governed by a contractor's past experience with similar work activities, derived from baseline production rates (Pellegrino, et al., 2012).

Supporting the concept of using data to inform business decisions and aid project management, a recent report from KPMG stated that 83% of industry executives feel that organisations will be data-driven in the future, with data analytics and predictive modelling used routinely for project planning and modelling (Armstrong, et al., 2019). However, the industry has not arrived at this point yet; Jepson *et al.* (2019) hold that, despite the advances in the industry, many core construction technologies and systems have remained largely unchanged since the 1950's, echoing Farmer's (2016) criticism of the industry's cultural resistance to chance. Perhaps it is indeed time for a change?

1.4 Thesis Layout

This thesis is laid out as shown in Table 1-2 below.

Table 1-2. Thesis Layout

Chapter 1. Introduction This chapter introduces the thesis, outlining the gap in knowledge and gives the general foundation for the research.
Chapter 2. Industry Background This chapter provides justification for the study and explains the research problem of inaccurate planning in the construction industry. The practice of planning and scheduling is reviewed from tender stage through to construction, including progress and productivity measurement.
Chapter 3. Literature Review The purpose of this chapter is to provide a theoretical foundation to the industry-based research problem identified in Chapter 1, critically reviewing current academic thinking on the problem through an analysis of the extant literature.
Chapter 4. Synthesis and Conceptualisation Chapter 4 has been written in order to consolidate the findings of Chapters 2 and 3 and develop an approach to answer the research question.
Chapter 5. Methodology This chapter describes the research methods used to perform the study, including the methodological approach and the methods used to collect and analyse data.
Chapter 6. Collection and Analysis of Quantitative Data The focus of this chapter is to analyse and present the primary data collected through a questionnaire survey.
Chapter 7. Unobstructive Research This chapter presents an analysis of six RC frame schedules, calculating the productivity rates for reinforcement and formwork installation and slab cycle times.
Chapter 8. Interviews Chapter 8 presents the results of seven interviews, where practitioners' views were canvassed on progress measurement, progress data and decision making.
Chapter 9. Validation of a Planning Tool This chapter collates the data gathered in previous chapters and utilises it to inform the creation and use of a knowledge database to predict task durations. The novel sets of coding to collect, store and use production data are described here as well as the series of tests performed on the tool.
Chapter 10. Conclusions and Recommendations This chapter provides conclusions and recommendations drawn from the research, providing recommendations for further development and study.

The following chapter will discuss the general problem in industry and provides a state-of-the-art review of planning and scheduling in RC frame construction.

2 Industry Background

2.0 Introduction

The purpose of this chapter is to identify the general problem in industry as inaccurate planning and scheduling and then consider this problem in terms of RC frame construction. The aim of this thesis is to produce a novel tool to enhance construction project management by improving construction schedule accuracy in RC frame buildings. To achieve this aim, it is necessary to understand the existing practices employed to produce construction schedules, and how planning decisions are made by the planner. The problem in practice is firstly identified, with a description of RC frame construction then presented, including a discussion on the types of schedules produced in this sector and how production rates for formwork erection and reinforcement installation are evaluated. The measurement of performance is then reviewed, including a discussion on how bias can influence this process, followed by a description of how planning is undertaken in practice. The chapter will conclude by identifying the research question and the associated research problem.

2.1 Identification of the Problem

The construction industry is a significant economic sector in most countries, with between 9% and 15% of total Gross Domestic Product (GDP) allocated to the built environment (Asadi, et al., 2020). In monetary terms, according to a recent report by Statista (Wang, 2019), the global spend on construction was £9.3 trillion in 2018 and is expected to reach £10.5 trillion by 2022. In the UK, the House of Commons Library indicates that annual construction turnover is 6% of GDP at £117 billion, employs 6.6% of the workforce and includes 13% of VAT-registered businesses (Rhodes, 2019). It can be seen, therefore, that the construction industry is a significant contributor to the UK and worldwide economy. Despite this importance, the construction industry has a reputation for unpredictability and delivering projects late, something the Farmer Report (2016) recognised:

> '*There appears to be a general acceptance of failure and underperformance both by industry itself but also begrudgingly by clients.*'

Farmer (2016) is also critical of the culture of 'reactively masking preventable failures and poor planning', although McKinsey & Company is more forthright, criticising the construction industry for relying on claims and change orders to make up for the loss in revenue due to price or time shortcomings (Barbosa, et al., 2017). Schedule underperformance is a universal problem in the construction industry, as confirmed by a recent KPMG report which found that only 78% of projects globally achieve 90% of the planned schedule (Armstrong, et al., 2019). Construction delay statistics for the UK show only 59% of projects are delivered on time (Glenigan, 2019) and, unsurprisingly, the vast majority of UK construction companies, at 85%, have experienced delays on recent projects (Cornerstone Projects, 2017).

In an earlier study, the CIOB (2008) found only 33% of high-rise projects (those with seven or more storeys) were delivered on time, compared with the timely delivery of 71% of low-rise projects. This is considered by some as an indication of the complexity of the construction of high-rise buildings and underlines the requirement for a high standard of project planning and control to achieve project success (Farmer, 2016). As the majority (75%) of high-rise buildings in the UK are constructed using reinforced concrete (Council on Tall Buildings and Urban Habitat, 2020), it therefore follows that high-rise RC structures are a significant component of the construction industry and frequently experience construction delays, borne out by the researcher's industry experience. In addition to the difficulties in the execution of construction schedules, it has been found in industry that there are differences between the planned and achieved project durations due to incorrect construction schedules. Industry experience also shows that delays are common, with the late delivery of RC frame projects blamed on factors such as high winds, logistics, labour shortages or traffic congestion, however these delay factors are sometimes considered as symptoms of poor planning as they are not unique risks and are repeated frequently.

The severity of the delays on high-rise buildings was also investigated by the CIOB (2008) and it was found that 18%, or almost 1 in 5, high-rise building projects were completed more than 6 months later than planned, although delays of this magnitude are not normally experienced in practice solely due to delayed construction of the RC frame. This contrasts with low rise building projects, where it was found that only 1% were completed more than 6 months late (CIOB, 2008). The impact is realised through an increased financial burden, where an additional cost of up to 10% is encountered on 31% of delayed schemes (Cornerstone Projects, 2017).

Construction planning involves establishing the project goals and setting a realistic and usable time schedule for all tasks, ensuring work is completed in sequence, within the time and cost allowed, determining the resources needed to perform the tasks scheduled (Nguyen, 2020). Serrador (2012) states that planning and analysis are crucial to project success and identified that there is a direct positive correlation between these tasks and the reduction of risk, where poor planning leads to failed projects. A primary outcome of the planning process is the production of a robust construction schedule, recognised by many writers as one of the critical factors required to ensure project success (Stoy, et al., 2007; Derbe, et al., 2020). Al Nasseri *et al.* (2016) agrees, believing that, whilst scheduling is a discrete process with unique characteristics, it remains an integral part of the planning process and as it is one of the most crucial tasks in project management it must be undertaken by competent personnel. This view is supported by Pellegrino *et al.* (2012), where they state that appropriate planning and control are prerequisites for successful performance, making it incumbent on the contractor to undertake careful and rigorous planning, which should be guided and controlled by the contractual compensation arrangements such as staged payments or the threat of liquidated damages linked to key construction schedule dates. In spite of this clear requirement for accuracy, it is widely accepted that the prediction of construction schedules is not an exact science (Ke & Liu, 2005; Flyvbjerg, 2014; Sroka & Radziszewska-Zielina, 2016), with the lack of precision causing construction schedules to be inaccurate where project durations are frequently underestimated, which has regularly been experienced in industry. Furthermore, research undertaken by Parthasarathy *et al.* (2017) found that a lack of planning is the most critical factor affecting the productivity of both labour and equipment.

Zou *et al*. (2007) hold that there are many unique features of construction projects, such as protracted schedule periods, complex processes, difficult environmental influences, the dynamic nature of project teams and diverse stakeholder interests that collectively make the delivery of projects on time very challenging. In fact, research by Aibinu and Odeyinka (2006) shows that delays in construction may be regarded as an inevitability. Previous investigations into the causes of construction delay, such as those conducted by Sambasivan and Soon (2007), and Yaseen *et al*. (2020), found that the dominant source of delay was the contractors' improper or ineffective planning. One prominent cause of poor planning found in industry is linked to the planners' use of inadequate reference outputs and durations for site activities, where it has been found that the reference material used typically contains insufficient detail. Confirming this, Hsu *et al.* (2017), in their study of the root cause of construction delays, reported that planners have insufficient information to establish the construction schedule, and this factor, augmented by a lack of experience, was the primary influence in construction schedule delays as the planner must therefore estimate labour outputs and task durations.

Critical of human decision-making, Sample (2015), in his exploration of the reasons for the inaccuracy of contractors' construction schedules, believes the leading explanation is that humans have imperfect mental processes. It is argued by Sample (2015) that estimates and forecasts become biased when planners think intuitively, leading to human errors of judgement in the prediction of durations. Budzier *et al.* (2018) support this position, believing that there are various factors which contribute to schedule inaccuracy, with systemic deficiencies in planners' decision-making cited as the prime source of schedule delay.

The aforementioned deficiencies in information on labour outputs is exacerbated through variable workforce productivity, to the extent that it is considered by some to be the main cause of time overruns, promoting project delay due to lack of productivity. For instance, Pellegrino and Costantino (2018) believe that the main reason for construction schedule delay is not directly due to the construction schedule, but due to poor productivity of the workforce. This is supported by Pardo-Ferreira *et al.* (2020), where they state that the majority of operations in construction are human activities which are characterised by their high variability and potential to change. The challenge, therefore, is for the planner to understand the true level of productivity achieved on site and incorporate this into the construction schedule. These difficulties are reflective of current practice, where variances have been found between the assumptions made by different stakeholders, including estimators, planners and project managers, on the production rates achieved for certain tasks on site, between organisations (Proverbs, et al., 1998) or even within the same organisation (Talbot & Kapogiannis, 2016). This uncertainty regarding project control, and the consequential effect on schedule accuracy, is the broad gap in practice identified in this research.

2.2 Research Background

Having established that the planning and scheduling of construction projects is a difficult process, prone to inaccuracy and error, a description of RC frame construction is provided below, followed by an explanation of the gap in practice with regard to the scheduling of reinforced concrete frame construction.

2.2.1 Description of RC Frame Construction

RC frame construction typically comprises of the construction of concrete floor slabs supported on concrete walls and columns, consisting of four operations in the following sequence (Wang & Azar, 2019):

1. Erection of formwork
2. Reinforcement installation
3. Concrete placement
4. Removal of formwork

These tasks are performed by three trades, namely formwork carpenters, steel fixers and concrete finishers. Formwork is known by a number of different names, depending on the context and purpose. When constructed as part of the temporary works to the underside of a floor surface, it is commonly known as decking, typically comprised of 18mm thick plywood on a support system of beams and props. When formwork is constructed in a vertical orientation such as to walls, columns, upstands, down-stands, beams, stair flights and floor slab edges, folds or steps, formwork is usually referred to as shuttering. Irrespective of whether it is installed as horizontal decking or vertical shuttering, formwork is defined in this research as a mould to accept fresh, fluid concrete.

Some writers, such as Chandrangsu and Rasmussen (2011) or André *et al.* (2018) make a distinction between the formwork and the falsework, identifying the falsework as a system of supports under the formwork in the temporary condition. However, according to Jarkas (2017), formwork includes the surfaces in contact with the fresh concrete, as well as all of the necessary supporting temporary works structures. As the erection of falsework and formwork is undertaken by the same trade, that is, formwork carpenters, in general terms, Jarkas' definition of formwork will be used in this research.

There is a variety of materials available for RC slab formwork, such as timber, steel, aluminium, glass fibre reinforced plastic (GRP) and combinations thereof, with the choice influenced by the building design, material cost, site constraints, resource availability and contractors' experience with the available systems (Jarkas, 2017). Notwithstanding this, the most common material used for formwork in the UK is timber, or 'traditional' formwork, on an aluminium or steel system scaffolding or shores. Erecting the formwork is the first operation undertaken when constructing a reinforced concrete floor slab, normally consisting of a steel or aluminium structure formed of vertical columns or props, connected to modularised bracing frames. The props have screw jacks at one or both ends to allow for height adjustment, accommodating variations in slab soffit levels. The assembled system then provides support to a series of primary beams, which in turn support a secondary grillage of timber or aluminium beams (Reynolds, et al., 2017). When the system is assembled to the correct height and position, plywood timber sheets are fixed to the grillage of secondary beams forming a deck to receive reinforcement, cast-in items such as embedded cladding connections or electrical services, and ultimately concrete.

When the formwork is completed, the reinforcement installation commences. Taking the form of circular steel bars in a range of diameters, reinforcement is normally either straight or factory bent to standardised shapes (British Standards Institution, 2005). The reinforcement is arranged by steel fixers in a predetermined pattern, usually in two or more layers as designed by the structural engineer. The reinforcement material cost accounts for a significant portion of total project cost, with Zheng *et al.* (2019) reporting that for regular RC structures, reinforcement cost amounts to between 16% and 60% of the total project value, however in practice this is found to be less, something closer to 15%.

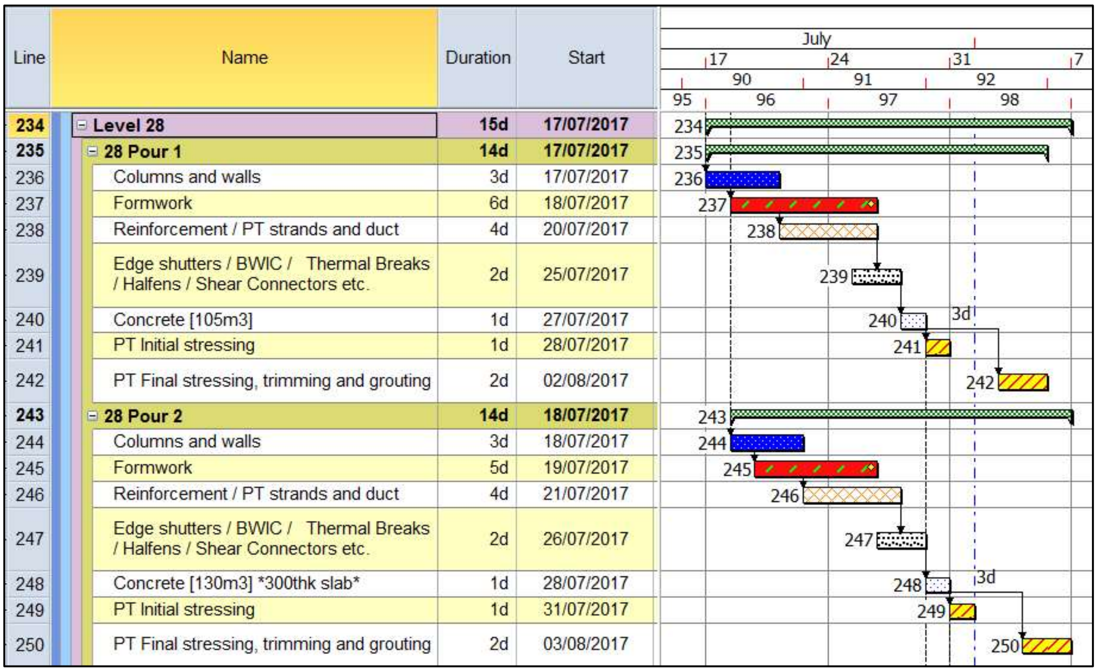
In addition to the capital cost of the material, the cost of labour to install the reinforcement is significant. The labour cost can be directly affected by the skill of the detailer, as their interpretation of the structural engineer's requirements to produce reinforcement layout drawings and corresponding schedules has a direct effect on productivity. Any reduction in the quantity of individual bars to be installed causes a reduction in the labour effort required, because each bar is manually placed and tied in position, or fixed, by the steel fixers. When the reinforcement is fixed in position, fluid concrete is then placed into the formwork mould, encasing the reinforcement and assuming the shape of the formwork. As the concrete cures and achieves strength, it gains capacity to carry the applied loads as well as its own self-weight, decreasing the potential formwork loads (Zang, et al., 2012). This allows the final task of formwork removal, or 'striking' to commence, permitting its re-use on upper floors and completing the process cycle.

2.2.2 Scheduling in RC Frame Construction

In construction, there are a number of different types of schedules generated to fulfil different functions, as acknowledged by Heesom (2004), and in practice, RC frame projects are no different, with three broad categories of schedule issued by contractors as follows:

- Tender schedules
- Construction schedules
- Occasionally, reactive schedules such as recovery or acceleration

Tender Schedules are the initial construction schedules compiled by the contractor, issued to the client at the tender bid stage. In order to fully understand a project, and to demonstrate this understanding, tender schedules should be created and presented to the client in a detailed format, addressing the needs of the project, rather than a high-level overview (Siami-Irdemoosa, et al., 2015). To achieve this degree of detail, the Project Management Institute (2017) recommends that the project should be decomposed into a hierarchical work breakdown schedule (WBS) of tasks. In the case of RC frame contractors this is usually to the level of each trade, such as formwork, reinforcement and concrete tasks, permitting full visibility and probity of the tasks involved. This level of decomposition has been found to allow efficient management of complex projects and to exercise control over the flow of resources through a project (Siami-Irdemoosa, et al., 2015). Refer to Figure 2-1, where trade operations such as formwork, reinforcement and concrete are displayed independently rather than aggregated as an RC floor slab. Links are created between tasks, maintaining interdependencies based on the sequence logic of the works, the flow of resource to ensure workforce continuity, and other constraints such as logistic considerations, workforce holidays, design periods, lead times for Local Authority permissions and licences, and so forth.



Line	Name	Duration	Start
234	Level 28	15d	17/07/2017
235	28 Pour 1	14d	17/07/2017
236	Columns and walls	3d	17/07/2017
237	Formwork	6d	18/07/2017
238	Reinforcement / PT strands and duct	4d	20/07/2017
239	Edge shutters / BWIC / Thermal Breaks / Halfens / Shear Connectors etc.	2d	25/07/2017
240	Concrete [105m3]	1d	27/07/2017
241	PT Initial stressing	1d	28/07/2017
242	PT Final stressing, trimming and grouting	2d	02/08/2017
243	28 Pour 2	14d	18/07/2017
244	Columns and walls	3d	18/07/2017
245	Formwork	5d	19/07/2017
246	Reinforcement / PT strands and duct	4d	21/07/2017
247	Edge shutters / BWIC / Thermal Breaks / Halfens / Shear Connectors etc.	2d	26/07/2017
248	Concrete [130m3] *300thk slab*	1d	28/07/2017
249	PT Initial stressing	1d	31/07/2017
250	PT Final stressing, trimming and grouting	2d	03/08/2017

Figure 2-1 Schedule extract

The **Construction Schedule** produced and issued to the client is a contract document with achievable completion dates. Typically, an evolution of the tender schedule, the construction schedule will include additional detail to incorporate any design development or new information received from the tender stage. For example, the sequence of works is updated to include revised or previously unknown information, as in practice, the information provided at tender stage is incomplete. The tender schedule is also sometimes shortened through negotiation where the risks covered by the float or buffer are assessed, and where appropriate, adjusted accordingly. Float is additional time apportioned to a task, included to account for the risk of unknown delays and unforeseen events such as inclement weather, mechanical break-down and unavailability of resource. For example, high winds can inhibit crane lifting operations to service the superstructure, causing a suspension of working at height, therefore it would be expected that there is an allowance in the schedule to accommodate wind delays. On occasion, risks will be shared or commuted to another party, removing the need for enhanced float. An instance of this would be where the Client agrees to a reduction in the severity of the penalty clauses for liquidated damages (Greenwood, et al., 2005), reducing the contractor's desire for terminal float. Look-ahead schedules are medium-term plans for project activities, produced by the Planner or Project Manager, extracted from the construction schedule. Usually spanning four to six weeks, the work is broken-down into smaller sections, selected to suit the size of the work crew (also known as 'gang' or 'squad'), the category of work, machinery types and other resources. Each workforce crew is then allocated to a task, giving direction and control to the Section Managers. Ideally the Section Manager or Construction Manager is canvassed for their input, ensuring they subscribe to the proposed construction schedule sequence and duration. This collaborative planning approach was described by Daniel *et al.* (2017) as being somewhat akin to the Last Planner system in Lean Construction, where the most reliable project plan, or construction schedule, is produced by the supervisor or manager responsible for the plan's implementation, that is, the 'last planner' (Heigermoser, et al., 2019).

Recovery and Accelerated Construction schedules are revised Construction Schedules, where time has been lost and needs to be recovered, or where works are required to be completed in a shorter timeframe, often for a financial incentive. The recovery or acceleration is usually achieved through a reassessment and rescheduling of the priority and sequence of each element of the works. According to Moselhi and Roofigari-Esfahan (2013), resource availability is the most important consideration to enable compression of the construction schedule by extending working hours, reallocating existing or introducing additional resources, or a combination of these factors, although Choy and Ruwanpura (2006) caution against the over-supply of labour in an effort to enhance productivity when erecting formwork, warning that crowded work areas actually reduce productivity, something evident in practice.

2.2.3 Production Rates

As outlined above, there are a number of different construction schedules produced by RC frame contractors, stemming from the Tender Schedule. This underlines the requirement for accuracy and the need for a comprehensive and precise construction schedule at tender stage, to mitigate the risk of inaccuracy in subsequent construction schedules based on the tender schedule. According to Pellegrino and Constantino (2018), a key variable to be considered when producing a construction schedule is the production rate or output rate of site labour. Also known as productivity, the output rate is the amount of goods and services a worker produces in a given amount of time (Pellegrino & Costantino, 2018). In RC frame construction, the output rate is measured in units produced per worker per day. Similar to the RC frame productivity formulae offered by Nguyen and Nguyen (2013), Jarkas and Horner (2015) and Jarkas (2017), the output rate for formwork installation to a floor slab is given as follows:

$$O_F = \frac{Q_F}{E} \qquad \textit{Equation 2-1}$$

Where, O_F is the formwork carpenter output, Q_F is the output quantity in m^2, and E is effort in days. The effort is also known as the carpenter-days or carpenter-hours and the units for formwork carpenter output are usually expressed as m^2/carpenter/day.

Equally, the output rate for reinforcement installation is shown in *Equation 2-2* below, and has units of kg/steel fixer/day, or tonnes/steel fixer/day:

$$O_{SF} = \frac{Q_{SF}}{E} \qquad \textit{Equation 2-2}$$

Where, O_{SF} is the steel fixer output, Q_{SF} is the output quantity in kg, and E is effort in days.

A further metric used to evaluate productivity is the floor cycle time or Slab Cycle Time. The cycle time is the amount of time taken, expressed in days, to complete one full set of tasks in repetitive construction activities (Pellegrino & Costantino, 2018). In RC frame projects, Jarkas (2017) describe the tasks in a floor cycle as the formwork set-up and installation, reinforcement set-up and installation, concrete placement and formwork removal. In common with Matthews *et al.* (2015), this research considers the floor cycle to include the installation of vertical members such as RC walls and columns as they are frequently a WBS component for floor construction activities in RC frames.

The construction duration of typical walls and columns supporting a floor slab is shorter than the erection of the slab formwork (Gavili & Mortaheb, 2015), due in part to their smaller size and advances in method such as prefabrication of the reinforcement and formwork which are then placed into position by crane (Midland Steel, 2019). Consequently, the construction of vertical members is ideally overlapped by the construction of the formwork and is normally on the critical path of the project for only one or two days per cycle. On site, once the floor slab is concreted, the following day the columns and walls are erected, with formwork erection commencing on day 2 of the floor cycle.

Understanding the floor cycle time in a project is crucially important as it is a measure of the overall production rate, as well as the overlap of the tasks, and any improvement in the cycle time creates an overall construction schedule improvement. Consequently, the planner's understanding of these labour productivity levels and slab cycle time is critical to the compilation of a robust project schedule. As the output rates are not normally clearly identified in project reports, it is therefore proposed that the true output rate is measured and this knowledge gain is used to inform tender schedule task durations (Talbot & Kapogiannis, 2016).

2.2.4 Measurement of Performance

Progress measurement is recognised as an essential on-going task on all construction projects (Braun, et al., 2015) and comprises of periodically measuring the actual progress on site and comparing it with the planned or expected progress (Mahami, et al., 2019). Whilst accurate and comprehensive progress monitoring is required, experience shows that traditional monitoring methods are inaccurate, ineffective, time-consuming, too infrequent, non-systematic, and do not facilitate the communication of progress information with sufficient speed. Furthermore, several studies have also shown that, in practice, organisational learning from construction projects is a rare occurrence, and on the occasion it does happen, there is a failure to deliver the intended outcomes (Fuller, et al., 2011; Duffield & Whitty, 2014; Yap, et al., 2017). Yap and Skitmore (2020) agree with this view, indicating that the collection of performance data from multiple projects can be leveraged to improve project time outcomes. Standard output rates are published by a number of companies and trade organisations, such as the Spons guides (AECOM Ltd, 2016) and BCIS (RICS, 2020).

However, published productivity data only represents the average productivity rates of the industry and not the specific performance of any particular contractor (Song & AbouRizk, 2008). As every company will produce slightly different output rates through the adoption of competing strategies and methods of work, the most precise means to determine task or activity performance is to accurately measure and record output data on site. It is noted that output data in the context of this research refers to performance facts that are observed or recorded, which are later analysed and converted into information.

Measuring progress is a diverse practice (Yang, et al., 2015), and, in practice it remains the most challenging task for a site manager due to the interdependencies of schedule activities and the complexity of project goals and drivers. Two major influences on the process of progress measurement are the biases of the person undertaking the measurement, and of the intended audience of the progress report. Measurement bias can occur due to subjective judgements and assessments of progress (Yang, et al., 2015). For example, when the contractor prepares a valuation of work done to make an application for payment from the client, an inspection of the works will be performed, prior to the date of the application for payment. This means the assessment will consist of a measurement of the work completed and a prediction made on how far the works will have progressed by the future date when the application will be made. Consequently, the person undertaking the progress assessment will fairly seek to measure the maximum amount of work done in order to legitimately maximise the valuation and therefore the payment. In addition, as progress is assessed throughout the duration of a project, it is inevitable that elements of work are incomplete when evaluated. Hence, there is a degree of subjective judgement used to establish the percentage complete of a piece of work or element of construction.

Furthermore, the assessment criteria can also affect the interpretation of reported progress. There is a difference between duration and effort, where duration is the time taken to complete a task, whilst effort is the amount of work required; the manner in which the progress is judged must be understood and communicated clearly. For example, if one floor of a building contains 20 similar columns, and 10 have been constructed, it is a fair judgement to consider that 50% of the column construction is complete, based on time and effort. In contrast, if a new basement is 12m deep, and it has been excavated to a depth of 6m, the basement excavation may be assessed as 50% complete. However, it may not be considered to be 50% complete by the Contractor, due to the remaining 6m depth requiring increasingly additional effort to excavate, such as alternative plant, equipment, temporary shoring works and the like.

With regard to the audience receiving the progress report, it is noted that there are often opposing opinions on the procedure for reporting progress, leading to selective reporting. For example, where the quantity surveyor may wish to maximise the current progress to maximise the payment application, the project manager may not wish to report, to an internal or external audience, the full extent of progress. In this instance, it is commonly found that, when a reporting period has been particularly productive, the project manager may under-report progress or engage in 'defensive reporting' (Keil, et al., 2019). This will allow a portion of the progress to be undeclared and reserved for a future period when output has not been so productive. Similarly, there is often a tendency to minimise the reporting of under-achievement. This is done with the aspiration of increasing output in the subsequent reporting period to overcome the current loss in progress and can be the result of an organisational climate of retribution, where there is a reluctance to report bad news, or the personality traits of the project manager where those that have a propensity for risk taking are more likely to misrepresent achieved progress (Keil, et al., 2014).

In another failing of the current monitoring process, it has been argued that there is a severe lack of up to date as-built information on construction projects (Navon & Sacks, 2007). Where the as-built data is not collected with a suitable frequency, some activities may be only recorded as 'complete' because their duration is shorter than the progress observation period. For example, if a task has a duration of three days, and the progress reporting period is monthly, the production rate for the task will not be known as it would only be identified as being completed within the progress period. Where information is out of date, such as a weekly progress report being viewed one week, or even one day, after it has been produced, there is a perception that the information is out of date, often with an expectation that further progress has been achieved. This implies a tacit understanding that the reported progress was accurate at the time of measurement only, possibly out of date by the time the report was produced.

The inaccuracies in measuring and reporting progress fosters opposing views on whether intermediate progress and overall milestones have been, or will be, achieved. Additionally, the conflicting methods of measurement interpretation and reporting create confusion for the planner where attempts are made to use past performance as an indicator of future project delivery.

2.3 Planning Synopsis

To give context to the study, a review of current professional practice was undertaken from within the planning department of a company operating as both a contractor and subcontractor in the construction sector that provides asbestos removal, decontamination, demolition, civil engineering and construction services, including the construction of RC frame structures. With a turnover of £100 million in 2019, approximately 75% of this revenue is derived from the core disciplines of demolition, civil engineering and construction. It employs a 600-plus workforce and a strong team of technically professional, specialist staff. Currently enjoying a client base that includes the most prominent national and international developers, investors, heads of state and royalty, it operates in the in the London area, generally within the bounds of the M25 motorway. The following review investigates how the organisation compiles project construction schedules, with the process of formulating a construction schedule within the firm explored, identifying how the different types of schedules, such as tender, construction and as-constructed schedules are produced.

2.3.1 Pre-Construction Phase

The tendering process commences when a tender pack of information is received from a client or their representative, inviting the Company to submit a tender offer for the works. The information is downloaded from a common data environment such as Aconex Viewpoint for Projects, Asite or similar (Bolpagni, et al., 2016), although at times a cloud data transfer service is used such as WeTransfer or Dropbox. The information is then checked for completeness and a decision is made based on a score card to bid for, or decline, the project. The scorecard ranks various influencing factors such as project type, location, value, payment terms, general risk profile, resource availability both to tender the project and to undertake the works, previous relationships with the client and client's team, contractual conditions, and the possibility of follow-on work. For projects where it is decided to offer a bid for the project, a Bid Launch meeting is held by the Bid Lead who presents the scheme to the Project Manager and the Heads of Planning, Estimating, Engineering and various other departments as required, depending on the nature of the project. A strategy is then decided on the commercial, technical and construction sequence approach to the project. Following the Bid Launch meeting, the Head of Planning designates one of the planners to produce the project tender schedule.

The planner will firstly review the tender documentation, including the Invitation to Tender, the Employer's Requirements and the Bill of Quantities. The drawings, specifications and client's BIM models are then reviewed and a 'scrap-book' of salient information is collected by the planner. The scrap-book is an electronic document containing extracts of the client's tender information of importance to the planning of the scheme, such as construction details, sequence information and specific planning requirements. The planner also uses online aerial and street mapping tools to view the location of the project, identifying local constraints such as bus lanes, cycle stands, taxi ranks and parking spaces, whilst a desk-top study is used to investigate the location of underground services, train lines and the proximity of watercourses.

When the construction sequence and strategy has been formulated by the bid team, the planner will commence compiling the schedule. A high-level schedule of works is created, developing the agreed sequence of the scheme. The planner then develops the WBS, calculating each task duration by drawing on a number of different sources. The principal sources include the client's BIM model, drawings and specifications from the structural engineer and architect, which are used to extract the geometric and physical properties of the concrete floor slabs under consideration. These sources, including output or productivity schedules, rules of thumb and instinct, allowing a calculation of the duration of each task. With regard to reinforced concrete floor slabs, the following method describes how the task duration are calculated.

The floor areas are divided into segments or pours, the size of which are normally guided by the volume of concrete or the design requirements (Wang & Azar, 2019). The target concrete volume per pour is generally 150-200m^3 as this volume permits sufficient time to place the concrete and apply surface finishes, such as brushing, trowelling or power-floating, in one working day. When the pours have been chosen, the plan area of the pour is either taken from the BIM model or measured from the 2D drawings in software such as Bluebeam or Adobe (Weber, 2017). For a pour, the volume of concrete, V_C, is calculated from the pour area or area of formwork, A_F, and the concrete thickness in the pour, t_C, as follows:

$$V_C = A_F \times t_C \qquad \textit{Equation 2-3}$$

With regard to the mass of steel reinforcement required, this is seldom known at the tendering stage, as projects are normally tendered from RIBA Stage 3 or 4 information (RIBA, 2020) and consequently the detailed design has not been completed. Thus, it is common to receive an indication of the reinforcement content from the structural engineer in terms of kilograms of reinforcement per cubic metre of concrete. For suspended RC slabs, the density is usually of the order of 110-

175kg/m^3. Therefore the mass of steel reinforcement, M_R, may be calculated as the product of the concrete volume and the reinforcement density, ρ_R, as follows:

$$M_R = V_C \times \rho_R$$ *Equation 2-4*

The height of the formwork is calculated by subtracting the concrete thickness, t_C, from the structural slab level, SSL_p, of the pour to find the soffit level of the pour. The SSL of the slab below, SSL_{p-1}, is then subtracted from this value to give the height of the formwork:

$$H_F = SSL_P - t_C - SSL_{P-1}$$ *Equation 2-5*

Following the calculation of the formwork height, an arbitrary factor is applied to the formwork duration to allow the calculation of additional time for the erection, proportional to its height. The additional duration is determined heuristically by the company's planner, and in the organisation where the practice was reviewed, the duration calculation increases time by a factor 50% every 3.5m. The output rate is closely linked to the number of operatives, as output is calculated per operative per day. In the case of formwork, the output rate is square metres of formwork per carpenter per day, with a typical value of 10m^2/carpenter/day, and for the reinforcement, the output rate is measured in kilogrammes of reinforcement per steel fixer per day, with a typical value of 1,000kg/steel fixer/day.

To calculate task durations, the area of formwork and quantity of reinforcement are divided by the product of the respective output rates and the quantity of labour, with the result is expressed in days. Where fractions of days are present, the duration is rounded-up to the nearest day to give a whole day duration for each task. The durations are therefore calculated using the two following equations:

$$T_F = \left\lceil \frac{A_F}{O_F \times L_{Carp}} \right\rceil$$ *Equation 2-6*

Where T_F is the time to install the formwork, A_F is the area of formwork, O_F is the output of formwork carpenters, L_{Carp} is the quantity of carpenter labour.

$$T_R = \left\lceil \frac{M_R}{O_R \times L_{Sfix}} \right\rceil \qquad \textit{Equation 2-7}$$

Where T_R is the time to install the reinforcement, M_R is the mass of the reinforcement, O_R is the output of the steel fixers, and L_{Sfix} is the quantity of steel fixer labour.

Two further tasks commonly featuring in the WBS are the construction of vertical members and the casting or pouring of concrete (Jarkas, 2017). The casting of a slab is taken a single event with a duration of one day and the erection of vertical members is assumed to be carried out at a rate of between 10 and 15 columns and walls per day, whilst lift and stair core walls are given an average of 4 days per core. It is notable that these durations were found to be based on the planner's rules of thumb rather than a calculated, scientifically-derived duration. However, as indicated in Section 2.2.3 above, the vertical members and core walls are not considered to be of the greatest importance in the overall floor cycle duration, which is the time to construct one floor slab including completing the verticals, formwork, reinforcement and concrete tasks. The calculations are usually undertaken manually using a hand-held calculator and the outputs obtained from the Standard Outputs spreadsheet compiled by the Head of Planning and is based on experience and rules of thumb. It is noted that there are many different views on the standardised outputs, with the Project Managers and Contract Managers having different opinions on the Standard Outputs given in the planning spreadsheet in Figure 2-2, which is the subject of recurring disagreements, leading to frequent schedule amendments prior to tender submission.

Drainage		
100-225mm clay/concrete/plastic, 1.5m deep, trench battered or stepped	15	m/day, short runs
100-225mm clay/concrete/plastic, 1.5m deep, trench battered or stepped	50	m/day long runs
100-225mm clay/concrete/plastic, 1.5m deep, trench battered or stepped	100	m/day with no connections
100-225mm diameter cast iron, 1.5m deep, trench battered or stepped	10	m/day average
Gas Membrane / DPM		
Depends on type, welded joints etc.	150	m2/day welded joints, etc.
	250	m2/day simple laps
Suspended Slab		
Typical Values		
Area	550	m2, but up to 800m2 depending on resulting concrete volume
Volume	150	m3, but up to say 250m3 per day depending on logistics, depth and surface finish
Reinforcement Density	150	kg/m3
Formwork Installation		
Traditional strike-and-erect	100	m2 / day / 10 operatives
Reinforcement fixing rate	1	tonne/day/fixer
Steel fixers for slab reinforcement	8	operatives
Concrete Gang	7	operatives, incl. pump driver
Allow for additional linesman for multiple set-ups or long distance pump (>50m)		

Figure 2-2. Extract from Standard Outputs spreadsheet

When the durations have been established, they are entered against the WBS in Asta PowerProject, a project planning software (Memon, et al., 2014). The sequence of work is then established and controlled through the application of logic links to each task, defining antecedents and descendants, including interdependencies and constraints between task locations, resource availability and other restrictions identified in the strategic approach review of the project. The software produces a Gantt chart of tasks, which is revised and improved as engineering solutions evolve. Float is then considered and may be introduced to accommodate risk as identified in a Project Risk Register. Float is also introduced to allow for factors such as groundwater removal, archaeological investigations or the time taken to achieve enhanced concrete finishes. In some instances, float introduced to permit future negotiation on the overall duration and cost of the project with the client. Here, the planner will be guided to extend the schedule duration to later fulfil a client request to shorten it, effectively presenting the true duration. The schedule is then completed, and the planner compiles a list of planning assumptions made, ensuring transparency of the schedule. When the tender construction schedule has been completed, an information release schedule (IRS) is compiled by the planner. This document outlines the latest date the design information is required from the design team to enable the works to progress and is a function of the construction schedule and procurement lead times.

At the same time as the construction schedule is being compiled, a 3D model is created in Revit, enabling virtual construction to explain construction methodology, sequence and logistics. The construction schedule and model are both imported into Synchro, a 4D visualisation software. Within this environment, construction schedule tasks are associated with model elements to create a 4D model of the project. This supports interrogation of the planned construction schedule construction time and validation assessments on the sequence and the constructability of the project, including workspace clashes and the flow of resources between work fronts.

It is noteworthy that the task durations, based on output rates, are originally chosen by the planner. However, as indicated previously, different planners, contract managers, project managers and estimators make different assumptions and use different output rates to calculate task durations. The output rates are based on various metrics, including rules of thumb and intuition, where output differences were unrecognised, unreported or accepted as a known planning risk.

2.3.2 BIM in Preconstruction

Projects are increasingly being scheduled and tendered using 4D BIM, where the Company has found that the use of a model at tender stage enhances design coordination and facilitates constructability. In particular, temporary works and enabling works are examined where the model is used to identify the optimum sequence and avoid clashes prior to the commencement of construction, mitigating costly delays and re-work, and identifying and reducing construction risks. The firm's approach is to construct a project in the virtual 4D world at tender stage, therefore ensuring, insofar as possible, that the construction process is 'right first time'.

The 4D BIM process begins during pre-construction and continues through the construction phase to support and manage site activities. There are a number of tangible benefits gained by operating in this manner, including enhancing the delivery team's awareness of the construction schedule, improving communication with all key stakeholders, better management of information, error and waste avoidance, enhanced navigation and creating an understanding of the spatial properties of the scheme, yielding greater stakeholder engagement. In order to facilitate this new method of project control, the organisation has invested heavily in software and training, developing new skills for those engaged in the modelling, tendering and delivery of projects. A key component of the company's BIM strategy is the formation of a team of architects and engineers to create 3D models suitable for the company's purposes, permitting a more efficient and streamlined process.

2.3.2.1 **BIM Process**

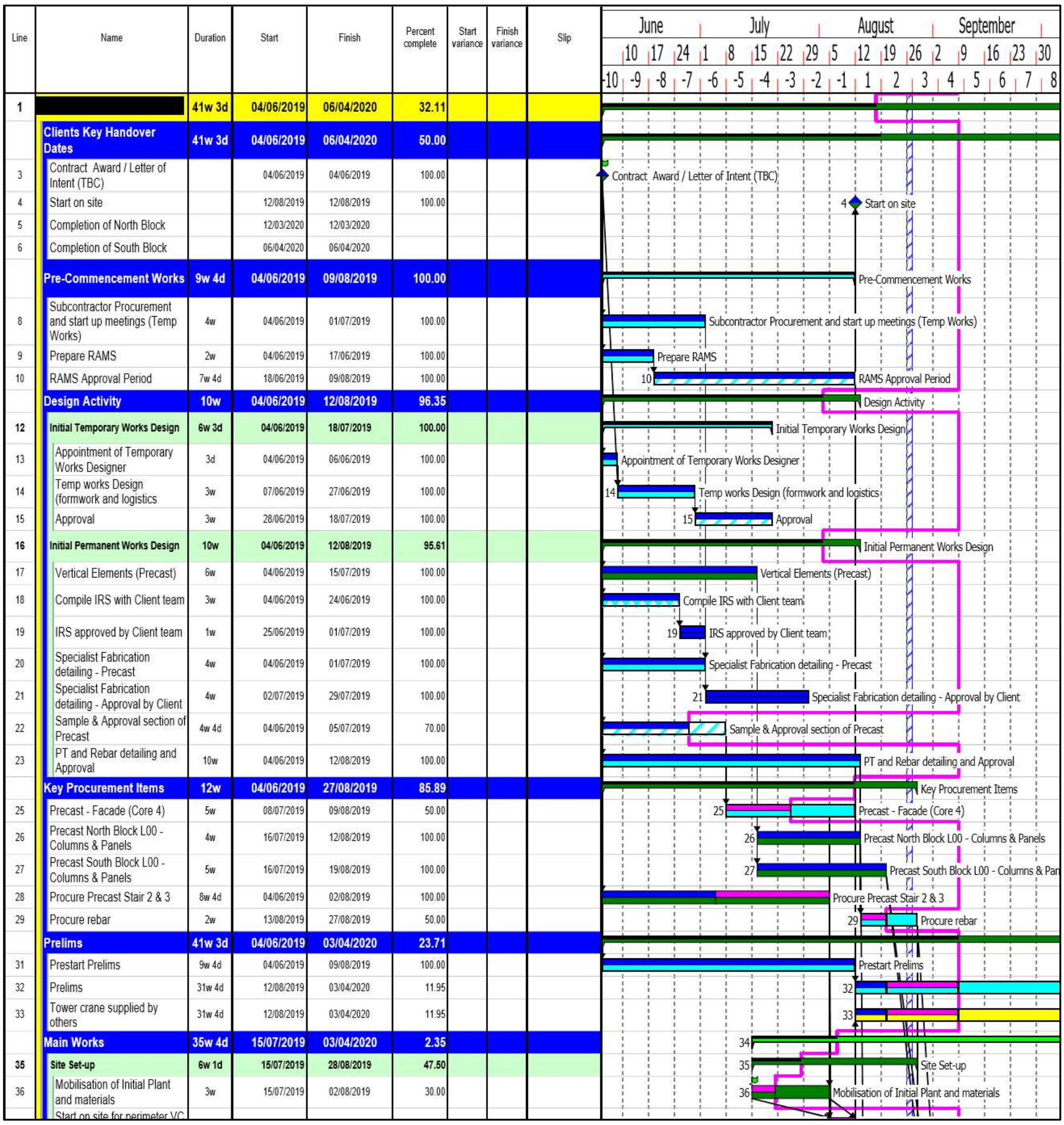
When a model is uploaded to BIM software, the model's elements are read, with the geometry interpreted and quantities then identified (Shou, et al., 2015). A quantity take-off is prepared from the model by the planner or estimator, generated from the volumes, surface areas, lengths, heights, position and mass, extracted from the metadata or calculated automatically from the model elements (Ma, et al., 2013). A prerequisite to the extraction of measurement data is to ensure that model components are assembled with a view to facilitating appropriate interpretation by estimating software. For example, the standard method of measuring columns is per floor (Lee, et al., 2014) but in practice columns are often modelled by structural engineers or architects from the ground floor to roof as a single element. This method of modelling affects the estimate and construction schedule, as the column would not be constructed as a single element but as individual columns at each floor level.

Furthermore, despite the increasing availability of models, it is noted that they are not always functional. Some contain a high level of detail with a vast degree of information and metadata, rendering them unusable on anything other than computers with superior processing power due to their large file size. Another common difficulty encountered is the prevalence of what is termed in the organisation as 'Hollywood BIM', were the model has a very low-level of detail and little non-graphical data rendering it useful as a viewing or marketing tool only, with the appearance of being a robust and substantial model. This experience is supported by Yoders (2010), where the difficulty of designers creating 'pretty' models is highlighted, recognising that the models may be incomplete and inaccurate.

2.3.3 Construction Phase

During the construction phase, the Project Manager, or Planner, will monitor the project and assess progress weekly for each construction schedule task and compare it to the agreed contract construction schedule within the planning software. To assess the amount of progress for suspended reinforced concrete slabs, the percentage of each element in the WBS is estimated. This includes counting the number of columns complete in each pour, then making a progress estimate for the number of columns under construction. The result is the percentage of columns complete for each pour, with an estimated allowance made for the partially-completed columns. For the assessment of formwork progress, the installed surface area of the formwork is measured either physically by means of a measuring tape or through the use of engineering instruments, with an additional allowance made for partially-erected formwork. When unable to measure the work produced, an estimate of the area is made through two methods. The first is aligning the constructed formwork with structural elements such as walls and columns and then referring to the plan drawings of the location under review, determining the area constructed. The second method is more suitable for rectangular surfaces, and involves counting the number of plywood sheets visible to the top of the formwork. The boards have standard dimensions of 1220mm x 2440mm, allowing a rapid estimate of the area of formwork erected. The reinforcement progress is more challenging to accurately estimate as it is difficult to gauge the mass of the installed reinforcement, although with experience a rough approximation can be achieved. A more accurate method is to assess the percentage of the overall reinforcement installed as a proportion of the floor slab and multiply this by the total reinforcement in the slab, with the result being the quantity of reinforcement installed.

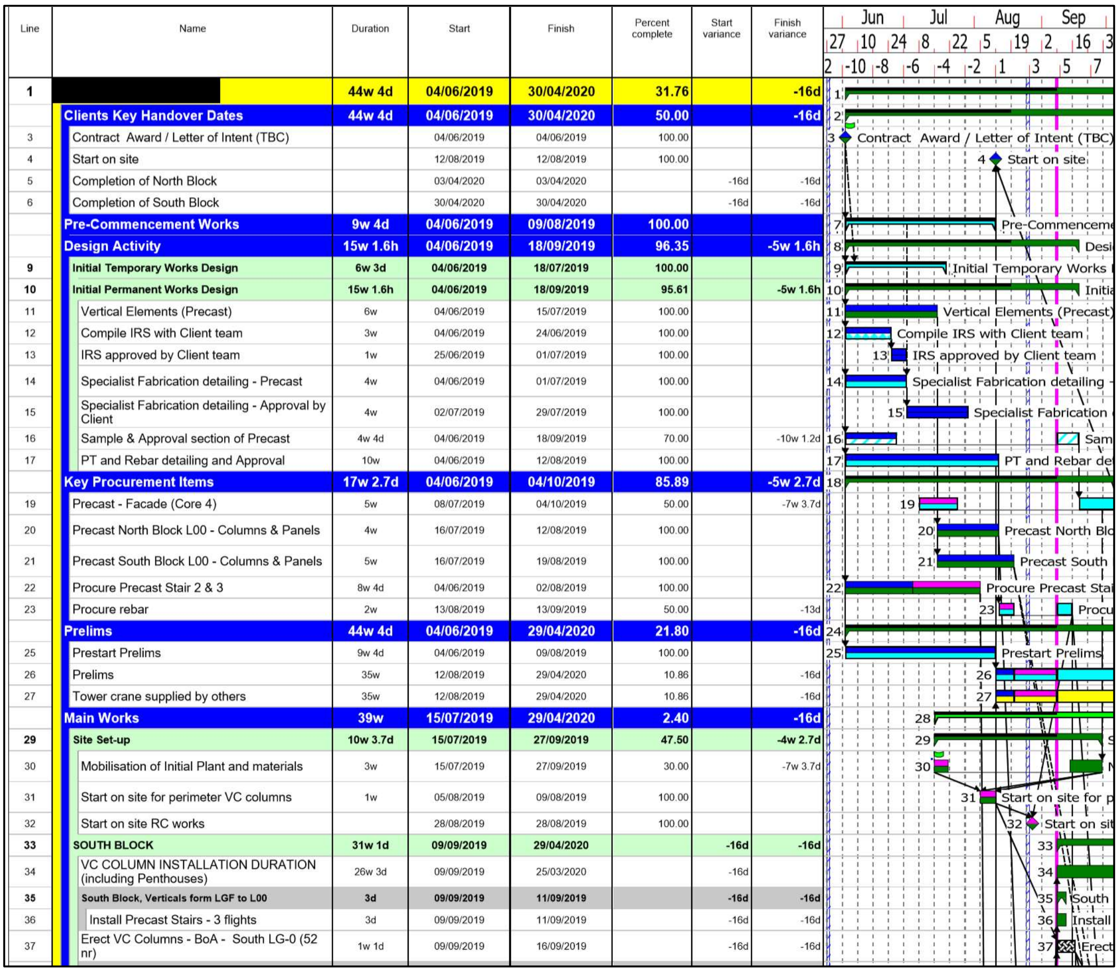
A similar approach is taken to the concrete installation, whereby the work done is considered as a percentage of the overall task. The work done can be interpreted in two ways, effort or time, although in most cases it is considered as time, so 50% of the task is complete when 50% of the duration is complete. The progress is then recorded in the planning software by entering a percentage complete of each task. This produces a ‘jagged-line’ indicator to illustrate the progress, as the example in Figure 2-3 below shows.



Line	Name	Duration	Start	Finish	Percent complete	Start variance	Finish variance	Slip
1	[redacted]	41w 3d	04/06/2019	06/04/2020	32.11			
	Clients Key Handover Dates	41w 3d	04/06/2019	06/04/2020	50.00			
3	Contract Award / Letter of Intent (TBC)		04/06/2019	04/06/2019	100.00			
4	Start on site		12/08/2019	12/08/2019	100.00			
5	Completion of North Block		12/03/2020	12/03/2020				
6	Completion of South Block		06/04/2020	06/04/2020				
	Pre-Commencement Works	9w 4d	04/06/2019	09/08/2019	100.00			
8	Subcontractor Procurement and start up meetings (Temp Works)	4w	04/06/2019	01/07/2019	100.00			
9	Prepare RAMS	2w	04/06/2019	17/06/2019	100.00			
10	RAMS Approval Period	7w 4d	18/06/2019	09/08/2019	100.00			
	Design Activity	10w	04/06/2019	12/08/2019	96.35			
12	Initial Temporary Works Design	6w 3d	04/06/2019	18/07/2019	100.00			
13	Appointment of Temporary Works Designer	3d	04/06/2019	06/06/2019	100.00			
14	Temp works Design (formwork and logistics	3w	07/06/2019	27/06/2019	100.00			
15	Approval	3w	28/06/2019	18/07/2019	100.00			
16	Initial Permanent Works Design	10w	04/06/2019	12/08/2019	95.61			
17	Vertical Elements (Precast)	6w	04/06/2019	15/07/2019	100.00			
18	Compile IRS with Client team	3w	04/06/2019	24/06/2019	100.00			
19	IRS approved by Client team	1w	25/06/2019	01/07/2019	100.00			
20	Specialist Fabrication detailing - Precast	4w	04/06/2019	01/07/2019	100.00			
21	Specialist Fabrication detailing - Approval by Client	4w	02/07/2019	29/07/2019	100.00			
22	Sample & Approval section of Precast	4w 4d	04/06/2019	05/07/2019	70.00			
23	PT and Rebar detailing and Approval	10w	04/06/2019	12/08/2019	100.00			
	Key Procurement Items	12w	04/06/2019	27/08/2019	85.89			
25	Precast - Facade (Core 4)	5w	08/07/2019	09/08/2019	50.00			
26	Precast North Block L00 - Columns & Panels	4w	16/07/2019	12/08/2019	100.00			
27	Precast South Block L00 - Columns & Panels	5w	16/07/2019	19/08/2019	100.00			
28	Procure Precast Stair 2 & 3	8w 4d	04/06/2019	02/08/2019	100.00			
29	Procure rebar	2w	13/08/2019	27/08/2019	50.00			
	Prelims	41w 3d	04/06/2019	03/04/2020	23.71			
31	Prestart Prelims	9w 4d	04/06/2019	09/08/2019	100.00			
32	Prelims	31w 4d	12/08/2019	03/04/2020	11.95			
33	Tower crane supplied by others	31w 4d	12/08/2019	03/04/2020	11.95			
	Main Works	35w 4d	15/07/2019	03/04/2020	2.35			
35	Site Set-up	6w 1d	15/07/2019	28/08/2019	47.50			
36	Mobilisation of Initial Plant and materials	3w	15/07/2019	02/08/2019	30.00			
	Start on site for perimeter VC							

Figure 2-3. Jagged progress line indicator

The impact of the progress on the critical path is then determined through a reschedule of the construction schedule. Rescheduling is the process where the software recalculates the sequence of the project, realigning works yet to commence to their future logical start date, taking into account the logic links in the construction schedule and the percentage of works completed. Referring to Figure 2-4 below, the rescheduled project may be observed, with the progress line (in pink) straightened and tasks realigned to their earliest date. As a consequence, the rescheduling process will identify any new critical paths due to the delayed work. When rescheduled, the differences between the planned start and finish dates and task durations are displayed as variance. This is a measure of the error in the forecast, which can be caused by a number of different reasons, including unforeseen project delays as well as scheduling errors and inaccuracies.



Line	Name	Duration	Start	Finish	Percent complete	Start variance	Finish variance
1	[redacted]	44w 4d	04/06/2019	30/04/2020	31.76		-16d
	Clients Key Handover Dates	44w 4d	04/06/2019	30/04/2020	50.00		-16d
3	Contract Award / Letter of Intent (TBC)		04/06/2019	04/06/2019	100.00		
4	Start on site		12/08/2019	12/08/2019	100.00		
5	Completion of North Block		03/04/2020	03/04/2020		-16d	-16d
6	Completion of South Block		30/04/2020	30/04/2020		-16d	-16d
	Pre-Commencement Works	9w 4d	04/06/2019	09/08/2019	100.00		
	Design Activity	15w 1.6h	04/06/2019	18/09/2019	96.35		-5w 1.6h
9	Initial Temporary Works Design	6w 3d	04/06/2019	18/07/2019	100.00		
10	Initial Permanent Works Design	15w 1.6h	04/06/2019	18/09/2019	95.61		-5w 1.6h
11	Vertical Elements (Precast)	6w	04/06/2019	15/07/2019	100.00		
12	Compile IRS with Client team	3w	04/06/2019	24/06/2019	100.00		
13	IRS approved by Client team	1w	25/06/2019	01/07/2019	100.00		
14	Specialist Fabrication detailing - Precast	4w	04/06/2019	01/07/2019	100.00		
15	Specialist Fabrication detailing - Approval by Client	4w	02/07/2019	29/07/2019	100.00		
16	Sample & Approval section of Precast	4w 4d	04/06/2019	18/09/2019	70.00		-10w 1.2d
17	PT and Rebar detailing and Approval	10w	04/06/2019	12/08/2019	100.00		
	Key Procurement Items	17w 2.7d	04/06/2019	04/10/2019	85.89		-5w 2.7d
19	Precast - Facade (Core 4)	5w	08/07/2019	04/10/2019	50.00		-7w 3.7d
20	Precast North Block L00 - Columns & Panels	4w	16/07/2019	12/08/2019	100.00		
21	Precast South Block L00 - Columns & Panels	5w	16/07/2019	19/08/2019	100.00		
22	Procure Precast Stair 2 & 3	8w 4d	04/06/2019	02/08/2019	100.00		
23	Procure rebar	2w	13/08/2019	13/09/2019	50.00		-13d
	Prelims	44w 4d	04/06/2019	29/04/2020	21.80		-16d
25	Prestart Prelims	9w 4d	04/06/2019	09/08/2019	100.00		
26	Prelims	35w	12/08/2019	29/04/2020	10.86		-16d
27	Tower crane supplied by others	35w	12/08/2019	29/04/2020	10.86		-16d
	Main Works	39w	15/07/2019	29/04/2020	2.40		-16d
29	Site Set-up	10w 3.7d	15/07/2019	27/09/2019	47.50		-4w 2.7d
30	Mobilisation of Initial Plant and materials	3w	15/07/2019	27/09/2019	30.00		-7w 3.7d
31	Start on site for perimeter VC columns	1w	05/08/2019	09/08/2019	100.00		
32	Start on site RC works		28/08/2019	28/08/2019	100.00		
33	SOUTH BLOCK	31w 1d	09/09/2019	29/04/2020		-16d	-16d
34	VC COLUMN INSTALLATION DURATION (including Penthouses)	26w 3d	09/09/2019	25/03/2020		-16d	
35	South Block, Verticals form LGF to L00	3d	09/09/2019	11/09/2019		-16d	-16d
36	Install Precast Stairs - 3 flights	3d	09/09/2019	11/09/2019		-16d	-16d
37	Erect VC Columns - BoA - South LG-0 (52 nr)	1w 1d	09/09/2019	16/09/2019		-16d	-16d

Figure 2-4. Rescheduled construction schedule with progress impact shown

2.4 Addressing the Problem

The foregoing text identifies the gap in knowledge relating to how to schedule correctly, which is manifested as discrepancies between the predicted and actual durations for their construction. The use of heuristics combined with inaccurate or conflicting output rates is clearly detrimental to accuracy demanding that an alternative, more accurate process is found. For instance, one survey found that 40% of respondents cited poor planning and unrealistic schedules as the primary cause of delay (Cornerstone Projects, 2017), underlining that the planning and scheduling process is currently flawed. Islam *et al.* (2019) believe that improvement is possible through the effective identification and assessment of risk and adopting appropriate risk management strategies, reducing reliance on judgement-based decisions which results in bias, inconsistencies and imprecision.

To bridge this gap and enhance accuracy, the productivity which has been regularly achieved on site for similar type of work must be reflected in the construction schedule. The state-of-the-art review illustrated that, whilst there is an awareness of inaccuracy in scheduling, the current process does not take steps to rectify these inaccuracies when compiling construction schedules. It is therefore necessary to perform a review of the literature, exploring the corpus in relation to the problem in an effort to understand how to measure, collect and use productivity data.

2.5 Summary

This chapter has identified the problem in industry as inaccurate planning and scheduling, which commences at pre-construction stage and continues through the duration of the project. An explanation of RC frame construction has been given, in particular the reinforcement and formwork components. A review of the planning and scheduling practices has been provided, highlighting the difficulties the planner experiences in obtaining accurate progress and performance information on which to base output projections.

The floor cycle time is mostly influenced by the amount of formwork required to the floor slab soffit as it is the most labour-intensive task and normally has the longest duration. Whilst the placement of concrete is standardised at one day, it has been established that there are conflicting assumptions regarding the output rates for formwork and reinforcement installation and slab cycle times. Accordingly, the RC frame planner's durations were frequently based on rules of thumb, experience and intuition. To overcome the problem of inaccurate construction schedules, this research aims to develop a tool to permit the collection of accurate data in a structured planning knowledge database, and use this data to predict future planning durations based on historical performance. This will enable the creation of more accurate schedules, at both tender and construction stage. More accurate tender bids will also be facilitated through schedule certainty, as risk will be better understood and controlled. Sharing of this information facilitates precision, transparency and accuracy in terms of progression monitoring, effectively building trust. This building of trust could be an efficient marketing tool, with potential economic ramifications.

A review of the extant literature is now undertaken in Chapter 3 to establish the theoretical underpinnings of this research and investigate current academic thinking on the problem of inaccurate construction scheduling. The literature will be assessed in terms of how planning is undertaken and how it can be improved, with a view to creating a procedure to improve scheduling accuracy.

3 Literature Review

3.0 Introduction

The purpose of this chapter is to provide a theoretical foundation to the industry-based research problem identified in Chapter 2, through an analysis of the current literature. This chapter will firstly define project management, followed by a review of construction planning and scheduling and their role in contractor selection. Scheduling inaccuracy is then investigated, including the work of Kahneman and Tversky and their views on the planning fallacy, followed by the introduction of Reference Class Forecasting which has been applied and popularised in the construction arena by Flyvbjerg (2018) as a measure to address inaccuracy in planning. The chapter concludes with a study of knowledge management in terms of data collection and Polyani's views on tacit and explicit knowledge (Polyani, 1958 republished 2005) and the management of knowledge in construction.

3.1 Project Management

Project management has been given many definitions by researchers and organisations and although they use slightly different language, most include the concepts drawn together by Fayol, who published a general theory of business administration in 1917 (Voxted, 2017). For example, in Fayol's model, the five elements of management were described as planning, organising, commanding, coordinating and controlling (Lamond, 2015), which are similar to, for example Mesly's (2015) '4 P's of project management' – power, people, process, plan. Project management professional standards are global and have an influence beyond the field of project management, according to Delisle (2019), and although each standard provides its own definition of what project management is, common threads are evident. For the most part, descriptions of project management include three components, which encompass (1) project definition, (2) planning, and (3) controlled execution. For example, according to the Association for Project Management (APM), project management is 'the application of processes, methods, skills, knowledge and experience to achieve specific project objectives' (APM, 2019), whilst the Project Management Institute (PMI) defines project management as 'the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements.' (PMI, 2020), whilst the British Standards Institute standard for Project Management, BS6079:2019 (BSI, 2019), defines project management as the 'planning, monitoring and controlling of all aspects of a project and the motivation of those involved in it to achieve the project's objectives'. It is noted that the

International Standard for Guidance on Project Management, BS ISO 21500:2012 (BSI, 2012), identifies project management as 'the application of methods, tools, techniques and competencies to a project'. Whilst this definition does not include a reference to planning *per se*, the planning element is embedded into the process groups through which project management is accomplished (BSI, 2012). It is therefore evident that a fundamental and necessary facet of project management is project planning, which is explored in the following section.

3.2 Construction Planning

The term 'planning' is vague and polysemic, having many definitions (Li, 2008), although the CIOB offers some clarity by describing project planning as an art founded in experience, a group process which requires contribution from all affected parties for its success (CIOB, 2018). Closely aligned with the CIOB's view of the planning process, the APM describes planning as an art and a skill rather than a science, is based on experience and is a team activity to determine a strategy (APM Planning, Monitoring and Control Specific Interest Group, 2015). Cooke and Williams (2009) elaborated to include forecasting as a predecessor to planning, where forecasting is looking into the future and planning involves making decisions based on these forecasts. This research shares the view of Neale *et al.*(2016) with regard to planning, that is the 'activity of working out what has to be done, how, by when, by whom, and with what, i.e. doing the job in the mind' (Neale, et al., 2016), but also includes the communication of that plan to others.

Wang and Azar (2019) point out that the importance of effective planning and scheduling has become increasingly evident as construction projects become more complex. This complexity demands realistic schedules to act as effective communication tools among project participants, facilitating correct resource allocation, cost estimation, project control and evaluation (Wang & Azar, 2019). Construction planning is not only the production of a schedule, it includes consideration of the wider context of cost, quality, health and safety, the environment and other factors such as design and production (Baldwin & Bordoli, 2014).

In addition to the various definitions and interpretations of what planning is, confusion also exists regarding the differences between 'program', 'programme', 'schedule' and 'portfolio' (Shehu & Akintoye, 2009). For example, Mubarak (2015) points out that in the United Kingdom, 'programme' has the same meaning as 'schedule' does in the United States, as defined by the PMI, where 'program' means a group of related projects. The UK-based CIOB disagrees, preferring to use the PMI terminology, albeit with the UK spelling ‘programme’, to indicate a number of related projects and the term ‘portfolio’ to indicate ‘a number of different projects and programmes that an organisation may be involved with‘ (CIOB, 2016). This position is contrary to recent research by Wang and Wu (2020), who deem that a ‘program is a portfolio of projects.’ In this thesis, to avoid confusion the terms ‘construction schedule’ and ‘construction programme’ will be used to mean the time-bound representation and narrative of a project typically in bar chart form commonly known as Gantt charts.

The time-bound bar-chart, or ‘Gantt Chart’ has been used in industry and the military for some time, first referenced in 1923 in a description of Gantt’s work (Clark, 1923), although similar production charts have been used in the early 1900’s (Gantt, 1910; Gantt, 1919; Weaver, 2012; Debicki, 2015). A primary advantage of Gantt charts is their simplicity and ease of understanding (Wilson, 2003), the main reason they have become a common method to represent the work breakdown schedule of a project. As they are a graphical representation of a project, the size, colour and type of histogram bar can represent different qualities of a task, such as criticality, percentage complete and task category. Gantt charts are also beneficial for smaller-scale projects as the entire project can be viewed on one screen or on a single page.

The Gantt chart in use today does have a number of shortcomings including the difficulty in appreciating precedence relationships from the bar chart when compared with precedence diagrams (Ballesteros-Pérez, et al., 2018). The bar chart scheduling technique is further criticised by Ballesteros-Perez *et al.* (2018) because it can only represent one possible scenario or course of events and when change occurs, a separate Gantt chart is required to examine each option. Furthermore, Gantt charts may not be used to determine probabilistic alternative paths, as each iteration may have different activities being performed with alternative durations and costs (Ballesteros-Pérez, et al., 2018).

The practice of project management received significant contribution from endeavours linked to the Space Race and the Cold War, such as the Polaris rocket programme which led to the development of the Programme Evaluation and Review Technique (PERT) in 1958, the planning tool which gained widespread popularity in the 1960’s and 1970’s. In addition to PERT, other significant project modelling methods include the critical path method (CPM) and line of balance (LOB).

CPM was developed in 1957 and is based on network analysis of the logic and sequence of activities where one activity commences as soon as its’ predecessors have completed (Garel, 2013). CPM is ideally suited to construction as it can continuously monitor multiple tasks and activities, such as flow of funds, continuous raw material purchases, and labour requirements (Ghadar, 2017). In the UK, CPM is the most prevalent planning technique and is recognised by the law courts a method to assess delays and damages in litigation (Parry, 2015).

CPM scheduling involves decomposing the project into a WBS, as indicated in the review of practice in Section 2.2.2, and connecting the activities in a logical sequence where each activity has one or more predecessor and successor logic links to other activities. The resulting logic-linked network is then analysed to determine the critical path, firstly by a forward pass, where the earliest possible start date of each task is calculated from the commencement of the project. Secondly, a backward pass is performed from the last task in the project, when the latest finish date is calculated for each task. Comparing the earliest start and latest finish dates determines the total float for that task, and where there is zero float, the task is on the critical path (Parry, 2015). This process is undertaken through the use of planning software in practice, and the results are displayed as linked tasks on a bar chart. The main advantage of CPM is that it identifies the critical path, allowing project managers to prioritise the most critical tasks to maintain the project duration and avoid focussing on those tasks that do not affect the completion date (Hammad, et al., 2020). The CPM has limitations, however, and has been criticised by a number of academics for inherent shortcomings such as inflexibility with regard to task duration (Heesom, 2004), the requirement for accurate time estimates (Ghadar, 2017), an absence of any consideration of resource utilisation or crew balancing (Olivieri, et al., 2018), and a lack of consideration of the stochastic and dynamic nature of construction (Parry, 2015).

PERT is essentially a tool to interrogate the likelihood of achieving deadlines and completion dates (Kenley & Seppanen, 2010), facilitating evaluation of the time and resources necessary to complete a project, offering a visual representation of the project as a network similar to CPM (Baldwin & Bordoli, 2014). One of the main advantages PERT retains over CPM is that it takes account of the optimistic, pessimistic and modal times for the duration of a task, which are then used to estimate the task duration, also permitting a calculation of the probability that the project may be completed by a particular date (Ghadar, 2017).

Li (2008) stated that the main difference between the CPM and PERT is that the CPM emphasises activity duration, whilst PERT focuses on probability of an event occurring on a future date. However, the two methods can be used simultaneously and complement each other, where the CPM may be used to determine the criticality of activities and PERT may be used as the analytical model to assist in establishing the logical sequence of activities (Badruzzaman, et al., 2020). PERT requires a minimum of ten events to enable calculation, although it can accommodate hundreds of events making it suited to large, complex projects. It requires a WBS to be established, with tasks and events arranged in sequence according to a logical set of rules which permits determination of the critical path and 'slack' or float per task (Kerzner, 2017). Similar to CPM, PERT has been criticised for lack of workflow and an inability to schedule continuous resource usage, a project scheduling drawback overcome by a further method known as the line of balance, or LOB (Olivieri, et al., 2018).

There are a number of types of **LOB**, such as flow line, linear flow graphs and Repetitive Scheduling Method (RSM). Repetitive activities that advance horizontally or vertically in different locations of a project, such as roads, pipelines, high-rise buildings and tunnels are known as linear construction projects (Tran, et al., 2020) and are not difficult to plan, but problematic to manage in terms of resource distribution (Ungureanu, et al., 2019). Lester (2014) recommends the use of LOB schedules in such projects, as 'Network analysis is essentially a technique for planning one-off projects'. A number of researchers support this view, (Kenley & Seppanen, 2010; Olivieri, et al., 2018; Ungureanu, et al., 2019) opining that networks or bar chart techniques, such as CPM and PERT, were inefficient in the management of linear projects, finding that the location-based process, such as LOB, offered enhanced control over the allocation of resources to perform repetitive tasks. The LOB is based on maintaining the continuity of resource usage through a project by managing the sequence and duration of activities.

The LOB chart represents the cumulative production versus time and is dependent on aligning production rates to achieve continuous flow. Each crew or trade is represented as a sloped bar where the thickness represents the duration for each crew to complete a single unit of their task (Ali, et al., 2019), with time on the horizontal axis and the number of work zones or fronts (such as floor level or height) on the vertical axis. It is possible from inspection of the LOB chart to identify the work zone, the duration for each crew in that work zone and the 'buffer' or duration gap between one crew and the subsequent crew in one work zone (Lester, 2014).

Irrespective of the method of planning and scheduling, the project management 'iron triangle' of cost, time and quality is consistently used to measure performance in the construction industry (Mellado, et al., 2020). In addition, a recent study by El-Kohly, (2019) found that the optimal client selection process of both contractors and subcontractors is based on a low price, then combined with five other factors, including the iron triangle components of quality and time, although Marzouk et al. (2013) state that the most important performance criteria should be quality and historic schedule delay factors. Historically, significant emphasis has been placed on cost alone, with the ‘lowest price wins’ philosophy prevailing, prompting Latham (1994), in his report into procurement in the UK construction industry, to question routinely awarding the lowest bidder and recommending that additional criteria should be included in the evaluation. More recent studies have also shown that bid price is not the most advantageous criterion for a contract award decision (Kong & Yaman, 2016; Rabie & El-Sayegh, 2017). El-kahlek *et al.* (2019) state that reliance on lowest price criteria as a determinant for contract award will usually lead to project risks in terms of time, cost and quality, a stance underlined by Arantes and Ferreira (2020), where the writers state that the highest frequency of delays was caused by awarding the project to the lowest bidder.

Based on the foregoing, it is therefore argued that project duration is a crucial factor in the clients’ evaluation and award process, influencing their decision whether to progress with a construction project or not, which is found to be the case in practice. Consequently, construction schedules are of vital importance to the work-winning process, securing future work and maintaining business for contractors and the wider supply chain. It therefore follows that the accuracy of tender and construction schedules is of paramount importance and is now examined in the following section.

3.3 Schedule Inaccuracy

Planning is a process of forecasting future events and outcomes which may contain uncertainties or unknowns, performed by assessing the future and making allowances for it by gathering opinions and facts, in order to formulate an appropriate course of action (Bragadin & Kähkönen, 2016). Inaccurate estimation has frequently been identified as one of the major causes of project failure (Flyvbjerg, et al., 2009; Chan & Kumaraswamy, 1997; Pinto & Mantel, 1990; Cornerstone Projects, 2017; CIOB, 2008) with Khamooshi and Cioffi (2013) offering the view that an increasing number of projects are failing for this reason, with fewer successful projects. According to Cunningham (2017), risks in construction projects are inevitable; impossible to eliminate completely, Cunningham holds that these risks lead to a condition ‘where outcomes are often uncertain’, rendering accurate predictions difficult.

Flyvbjerg (2014) recognises that planning is a difficult process to perform, but believes there is no such thing as a project failing to meet its' schedule; the only failure, according to Flyvbjerg, is to plan incorrectly. Chong, Lee and O'Connor (2011) argue that schedule inaccuracy is due to the assumptions made by the planner, where an ideal schedule is produced rather than an exact one, based on the limitations normally faced in projects of a similar nature.

3.3.1 Definition

According to Batselier and Vanhoucke (2017), accuracy is generally accepted as the principal criterion for the appraisal of the performance of forecasting methods, with stability and timeliness described as quality indicators of forecasts. Gannon *et al.* (2012) consider schedule quality in terms of the percentage change to the cost, the duration and the activity count from tender stage. Bragadin and Kähkönen's (2016) study makes the case that research surrounding the quality of construction scheduling is mainly concerned with methods and tools and devised a proactive technique to develop and check a project schedule for performance. The performance assessment was based on five key Schedule Performance Indicators, including Construction Process, encompassing activity duration where the duration of project tasks is essential to the correct compilation of a schedule (Bragadin & Kähkönen, 2015). Zhao *et al.* (2020) hold that schedule robustness should include two measures, the solution robustness, or the deviation of task start times, and the quality robustness, or the completion probability, whilst earlier research by Zhao *et al.* (2020) indicated that analysis of the planned and achieved start time and the deviation in logical relationships between activities are suitable determinants for schedule robustness.

Khamooshi and Cioffi (2013) hold the view that the planning and scheduling of construction projects rely on deep knowledge of past performance, using previous experiences to develop the duration of a schedule from task level durations. Their proposed unified scheduling method hinges on the planner providing estimates of individual task duration and combining this with an estimate of the error in their prediction based on historical production rates to achieve a more realistic overall project schedule. Whilst the authors recognise this approach does not solve the problem of inaccuracy, they suggest it reduces planning errors through the increased output analysis performed at task level.

3.3.2 Cause – Effect Analysis

There is often a disconnection between the outputs believed to be achievable at tender stage and what is actually achieved on site during construction (Li, 2008). Some researchers attest that the prediction of the duration of a task is based on a conceptualisation of a scenario or a mental simulation of how the task will unfold, rather than on how the task aligns with similar previous tasks (Hadjichristidis, et al., 2014; Wiese, et al., 2016; Kanten, 2011).

Vidhyasri and Sivagamasundari (2017) undertook a broad literature review involving the examination of 37 relevant articles and found that the planning, monitoring and control system was one of the most critical elements influencing construction scheduling quality. Debre *et al.* (2020) believe that there are a number of influencing features which can affect the quality of project planning and classify 'human' influence as a leading factor.

3.3.3 The Science of Planning

One element of the human influence in planning was identified in Section 2.3.1, where planners employ heuristics and instinct to carry out estimation decisions on schedule durations. Cognitive science has formed the basis for examining human decision making, viewing that memories, both episodic, or generated by personal experiences, and semantic, from learned knowledge, have a role to play during analytical and experiential processing when an individual is faced with a decision involving risk (Drost, 2013).

Love *et al.* (2019) perceive the human mind as a processor that attempts to make decisions using limited resources and therefore reliance is placed on easily accessible, rapid intuition (Wang, et al., 2019). Beliefs concerning uncertain events cause people to consider the probability of one event occurring or not occurring and to reach a decision based on the intuitive or heuristic judgement of probability, leading to cognitive bias. Kahneman (2011) discussed how to avoid heuristic errors, concluding that it is required to 'recognize the signs that you are in a cognitive minefield, slow down, and ask for reinforcement' by deliberately undertaking slow, logical, unemotional thinking. Kahneman recognises that this 'outside view' is simple in principle but difficult to execute, as humans do not fit into the traditional economists' view that they are rational agents (Tunstall & Beymer, 2017).

3.3.4 The Planning Fallacy

In their seminal publication *Judgment under Uncertainty: Heuristics and Biases*, Tversky and Kahneman (1974) showed that when individuals are making decisions in conditions of uncertainty, heuristics can lead to errors, stating ‘In general, these heuristics are quite useful, but sometimes they lead to severe and systematic errors’, later describing the condition as the ‘planning fallacy’ (Kahneman & Tversky, 1977). This viewpoint was explained further by the authors, (Kahneman & Tversky, 1979), where they theorise that people react differently to the potential for losses and the potential for gains, caused by a systematic fallacy in their cognitive decision process.

The theory was applied to the business field by Lovallo and Kahneman (2003), referring to the concept of the planning fallacy, where decisions are made based on ‘delusional optimism’ or optimism bias (Batselier & Vanhoucke, 2017). With optimum bias, there is a tendency for individuals to overemphasise projects’ potential benefits and underestimate likely costs, drawing positive reinforcement from success scenarios whilst ignoring the likelihood of mistakes. Likening optimism bias to viewing prospective projects through ‘rose-coloured glasses’, Lovallo and Kahneman (2003) proposed that individuals have a belief in achieving a desired reality rather than the most likely reality, chiefly caused by two cognitive biases: anchoring and competitor neglect. The anchoring bias, according to Lovallo and Kahneman (2003), is the condition where a reference point such as an initial estimate is given to a subject and then relied on, such as benchmark productivity from past projects. The competitor neglect bias is where the abilities and plans of competitors is ignored, with internal abilities and control over-exaggerated and credit taken for successful outcomes and blame apportioned to external factors (Lovallo & Kahneman, 2003). The planning fallacy leads to inaccuracy in estimates of costs, completion times and risks of proposed actions, where individuals overestimate the benefits of those actions (Flyvbjerg, 2013).

Pressures also exist within organisations where pessimism about overoptimistic projects is punished, and optimism is rewarded, in what Flyvbjerg (2018) titled strategic misrepresentation. It is advised that taking the ‘outside view’ will neutralise the cognitive biases and organisational pressures caused by the ‘inside view’, where awareness and an objective forecasting method are taken (Lovallo & Kahneman, 2003).

3.3.5 Measures to Address Inaccuracy

Hadjichristidis *et al.* (2014) in their exploration of the planning fallacy propose that it is due to the formation of a mental scenario or simulation of the prediction of how the task will unfold. The authors recommend addressing the planning fallacy through taking the inside view and understanding the conceptual process of unpacking tasks and breaking them down into sub-tasks or components, rather than how the task fits with comparable previous tasks. Consistent with this reasoning, other researchers found that the likelihood of the underestimation of future task duration decreases if the task is unpacked into subcomponents (Kruger, 2004), or if separate estimates of duration are made for different task segments (Forsyth & Burt, 2008; Kanten, 2011).

Roy *et al.* (2013) also support taking the inside view, stating that the number of remembered components of a task, and whether the task is relatively long or short, has greater influence on the level of bias in estimation of task duration than the approach of taking an outside view. Other writers hold the opinion that the planning fallacy occurs not because the memories of past event durations are recalled incorrectly, but because the memories are systematic underestimates of past duration. Therefore, whilst the durations of future events appear to be underestimated, it is because they are based on past events which have been underestimated (Roy, et al., 2005; Roy & Christenfield, 2007).

Love *et al.* (2019) propose that the planning fallacy is not the most accurate theoretical position to capture project behaviour, promoting the ‘principle of the hiding hand’ view of Hirschman (2015). The hiding hand theory argues that, whilst creativity and resourcefulness are underestimated, the difficulties of the prospective task are similarly underestimated to the same extent, thereby the two underestimations offset each other. Love *et al.* (2019) believe that planners’ underestimation of project forecasts should not necessarily be considered a disadvantage. On the contrary, Hirschman, according to Love *et al.* (2019) believes that the underestimation of project costs, risks and difficulties is beneficial to planners and managers as they overcome problems and ‘stumble into success’, profiting from the learning process. Piciotto (2015) supports Hirschman’s ‘ignorance of ignorance’ argument, claiming that ‘under uncertainty, lack of foresight is a blessing in disguise’.

Ika and Söderlund (2016) support the idea of Hirschman’s hiding hand competing with Flyvbjerg’s theories of planning fallacy and optimism bias to explain project behaviour. Flyvbjerg, on the other hand, is subjected to criticism by a number of academics for his rebuttal of the Hiding Hand theory. For example, Ika (2018) believes that the Hiding Hand is more prevalent in a set of 171 projects by a factor of four to one. Room also criticises Flyvbjerg for dismissing Hirschman's Hiding Hand too quickly and believes that Hirschman's research should be considered more broadly to obtain value from his approach (Room, 2018). Lepines (2018) also takes issue with Flyvbjerg and Sunstein (2016) for the method of assessing and 'disqualifying' the Hiding Hand theory, whilst Anheier (2016) accused Flyvbjerg and Sunstein (2016) of not acknowledging the broader problem of incomplete information. Anheier also took issue with the statistical tests used to examine the Hiding Hands principle, stating that Hirschman's theory is designed as a framework for economic development rather than the infrastructure projects Flyvbjerg and Sunstein (2016) used as a sample (Anheier, 2016). More recently, Love *et al.* (2019) are also critical of Flyvbjerg, opining that Flyvbjerg and Sunstein's (2016) 'fierce critique of Hirschman' is misguided, and that the Hiding Hand and the Planning Fallacy actually co-exist (Love, et al., 2019).

Although Flyvbjerg (Flyvbjerg, 2016) is in agreement with Love *et al.* (2019) and concedes that Hirschman's Hiding Hand principle does exist, it is described a special case and not a typical one. Flyvbjerg (2016) performs a statistical test on the hiding hand theory and determines that it is not a typical project behaviour with 80% of projects not displaying the hiding hand traits, the inverse of Ika's (2018) claim. Flyvbjerg also takes issue with the beneficial ignorance stance, stating that 'ignorance is bad' and leads to the pursuit of 'projects that should not have been started' (Flyvbjerg, 2016).

Fridgeirsson (2016), in a review of completed Icelandic transport projects, found the benefits of RCF to be inconclusive, as it provides only marginal gains on the current position, however Fridgeirsson concluded by stating that it is expected RCF will be adopted to reduce the occurrences of inaccurate forecasting and cost overrun. Themsen (2019) was more forthright in criticising RCF, stating that it failed to produce more accurate forecasts. Despite the criticism, the article concedes that the failings are in the implementation of the process, where the reference classes were selected using 'biased judgement' and allowed managers to be 'delusionally optimistic' about their estimates. The wisdom of crowds is a possible solution to the problems of reference class selection, where organisations can combine the wisdom of multiple individuals to generate superior results, as proposed by Eubanks *et al.* (2015). The wisdom of crowds is the phenomenon whereby aggregated judgements are more precise than a single expert in the crowd (Hong, et al., 2020), although the successful application of it as a solution to the problem of RCF is requires a diverse selection of experts in the field, which may not always be possible in practice.

Flyvbjerg (2013) agrees with Taleb's (2010) opinion that ineffectual planners are either suffering from optimistic bias, or engaging in deliberate misrepresentation in their forecasts, and advocates the use of RCF to 'curb delusional and deceptive forecasts'. Buehler *et al.* (2010) state that planners are optimistic, and the fallacy is manifested where they maintain their optimism even 'in the face of historical evidence to the contrary'. This delusional optimism causes managers to make irrational decisions rather than judgements based on gains, losses and probabilities (Flyvbjerg, et al., 2009).

Sample (2015) believes that there are additional responses to RCF available to mitigate the effects of the planning fallacy. These include actor-observer bias and imaging processes, the effects of group processes, and task segmentation. Actor-observer and imaging bias is where team members, or actors, take the first-person 'inside view', and the third-person 'outside view' perspective is adopted by an observer to be a 'friendly house pessimist', to remind the team of obstacles and potential difficulties, protecting against the potential for self-deception and optimism bias by the project team (Sample, 2015). The effect of group processes is where collaborative tasks, such as meetings by the planning team, tend to focus on success factors such as efficiently following internal goals and plans, rather than addressing impending obstacles. Sample (2015) opines that the unpacking and segmenting of tasks can aid in reducing optimism bias, similar to strategies favoured by Hadjichristidis *et al.* (2014) and Forsythe and Burt (2008).

Data from several sources propose that reference class forecasting, or RCF, is a solution to counteract the planning fallacy (Kahneman & Tversky, 1977; Lovallo & Kahneman, 2003; Flyvbjerg, et al., 2009; Goodwin & Wright, 2010; Flyvbjerg, 2013; Wiese, et al., 2016; Flyvbjerg, et al., 2018; Hetemi, et al., 2020), whereby an 'outside view' is taken of the decision to be made. This consists of (i) using the experience gained from similar, previous projects, (ii) considering the outcome of these projects, and (iii) distributional information about the project outcomes (Flyvbjerg, 2013). Awojobi and Jenkins (2016) support this view, attesting that the planning fallacy explains why costs and schedule risks are frequently underestimated. They state that the planners' decisions are particularly based on inside views, focussing on specific planned actions rather than outcomes of previous projects with similar features. To overcome the effect of the planning fallacy on construction scheduling, Awojobi and Jenkins (2016) suggest that planners take the outside view, basing their decisions on the analysis of data and parameters from comparable projects to develop the most likely outcome for the project schedule. The construction of an RCF is further explained in Chapter 4.

A number of professional bodies are patrons of the RCF concept, such as the Association for Project Management (APM, 2018), Project Management Institute (Liu, et al., 2010) and the American Planner's Association (Sample, 2015), as well as governments worldwide as a process to manage their megaprojects (Themsen, 2019). Despite the popularity of RCF, the process does attract criticism in terms of the accuracy of the prediction. One criticism is that rare events are not accommodated very well in the RCF process (Goodwin & Wright, 2010), where the argument is made that the reference class is a sample and therefore unlikely to contain rare events.

A further criticism is levied at the use of probability, where Derbyshire (2017) believes that it lulls users to believe that the uncertainty of the future has been tamed, based on our current knowledge on the relative outcomes of specific processes, or current information, or the dispersion of possible outcomes on present and past variance. However, this argument may be applied to any process which examines probability and applies it to an uncertain situation; once the user understands what the statistics are indicating, then the risk of misinterpretation is greatly reduced.

3.3.6 Outlying Events

Taleb advocates that robust planning should accommodate improbable events instead of naively attempting to predict their occurrence (Bennett, 2014). Taleb describes two models for human circumstance, as explained by Bennett (2014), Mediocristan, where statistical values are clustered around a norm and Gaussian bell curves are applicable, and Extremistan, where a single case may affect the overall distribution. Taleb warns against basing predictions of 'extreme events' on data clustered about a norm (Bennett, 2014). The reason for this is that an outlier, or extreme event, strongly impacts the mean and standard deviation, particularly if the distribution is considered to be normal or Gaussian. In addition, outliers are unlikely to be detected in small samples if the mean is used as a central tendency indicator (Leys, et al., 2013). To accommodate outliers, or extreme events, a statistical calculation termed the median absolute deviation is recommended (Taleb, 2010; Leys, et al., 2013).

Flyvbjerg (2013) identifies the difficulty of ignoring outliers and draws parallels with the process of RCF, where the planner's best estimate does not necessarily fall close the mean. Flyvbjerg *et al*. (2018) support the view that to assume the distribution is centred on the mean is incorrect, where a distribution of the references is not necessarily Gaussian, that is, it should demonstrate skewness and asymmetry or 'fat tails' as dictated by the empirical distribution, including outliers. This position is in agreement with Kahneman and Tversky's (1979) opinion that the complete distribution is included in the statistical analysis to achieve the preferred and most transparent option (Flyvbjerg, et al., 2018). Whilst there are critics of Flyvbjerg, optimism bias and RCF, as well as the Hiding Hand theory, there is little doubt that Flyvbjerg's approach reduces uncertainty and increases the likelihood of achieving an accurately planned project.

3.4 Potential to Bridge the Gap

The foregoing illustrates that there is a gap in practice to overcome, with regard to inaccuracy in construction scheduling, and it is proposed that it may be possible to bridge this gap through the development of a reference class process, enabling the compilation of more accurate construction schedules. Currently, RCF is rarely practiced in construction, and is unheard-of in the field of RC frame construction.

There is no readily-available tool or platform for creating reference classes in RC frame construction, and those reference classes that do exist in other branches of the industry are commercially orientated with no guidance to their implementation in RC frame construction duration. This research will develop a simplified application of RCF theory specific to RC frame construction, with the intention of providing planners with a more accurate forecast for construction durations. As outlined above, central to the RCF system is the development of a reference base of past performance, allowing a more accurate estimation of the future. The collection and analysis of past performance is reviewed in Section 3.5, Knowledge Management in Construction.

3.5 Knowledge Management in Construction

Song *et al.* (2007) defined knowledge management as the creation, storage, access and dissemination of intellectual assets, although the PMI (2017) offers a more specific definition with regard to project knowledge: 'managing project knowledge is the process of using existing knowledge and creating new knowledge to achieve the project's objectives and contribute to organisational learning'. As a discipline, knowledge management emerged in the 1980's, where the early focus was on the capture of internal knowledge (Blake, 1998), complimented by harnessing knowledge from outside the organisation to build value (Ruggles, 1998). The concept of external knowledge was built on by other writers such as Skapinker (2002), where the idea of utilising the external knowledge for internal benefit was highlighted, with the ideas and experience of clients and the supply chain viewed as essential to capture to improve an organisations' performance. The early view of 'capture, disseminate and use' was likened to information management and document control, focussing on the explicit knowledge available (Payne, 2014). This has been replaced with knowledge management becoming a more collaborative, interactive and innovative endeavour where employees are encouraged to share and create knowledge (Suorsa, et al., 2019), facilitated through organisational culture, although Payne (2014) recognises that the social act of sharing knowledge requires employees who want to learn, and others who want to share.

3.5.1 Formalising Tacit and Explicit Knowledge

Data, according to Sardar (2020), is a set of discrete facts, symbols or signals, representing objects and events such as an unordered list of times achieved by athletes in a marathon. Information is processed, structured, organised, sequenced and arranged data, providing order, functionality and usefulness. For example, data is converted into information if the times for each marathon finisher are categorised for gender, age and experience. Knowledge, on the other hand, is processed, analysed or synthesised information, where human insights, values and experience act as a framework to interpret the information and provide theoretical, practical or experiential explanations or understanding of a subject (Sardar, 2020).

Polanyi (1958 republished 2005) identified the distinction between explicit and tacit knowledge. Tacit knowledge is that which is possessed by, and embedded in, the individual. It is context-specific, existing in the mind of the holder, based on insights and experiences (Kazi, 2005). Egbu (2004) notes that tacit knowledge can be described in three categories:

1. Embodied knowledge, where the knowledge is integral to an individual's human body as a function of the environment
2. Embrained knowledge, existing exclusively in a person's brain
3. Encultured knowledge, which is embedded in a social context and cannot exist outside it.

Tacit knowledge is gained through interactions and direct engagement with the world, rather than from doctrinal propositions or formally expressed theories or hypotheses (Garrick & Chan, 2017). Academics have made attempts to categorise tacit knowledge, with three degrees of tacitness highlighted by Ambrosini and Bowman (2008), comprising of (1) inaccessible, unconscious tacit knowledge, (2) tacit knowledge that cannot be explained through the normal use of words but may be conveyed through metaphors and storytelling, and (3) unarticulated tacit knowledge that may be liberated through asking the correct question. Other researchers have found that there are three types of tacit knowledge: conscious, automatic and communal (Spender, 1993), whilst Andrews and Smits believe that there are also four types of tacit, including enacted information, accumulated information, apprenticed know-how and talent and intuitive know-how (Andrews & Smits, 2018).

Explicit knowledge is more tangible, capable of being codified in a ‘hard’ form (Nonaka & Takeuchi, 1995). It is specifiable and can be formalised, with access, storage and transfer of this type of knowledge achieved by corporate documents and databases (Loebbecke, et al., 2016). Loebbecke *et al*. (2016) hold that there may be four types of knowledge which can be tacit or explicit, namely automatic, collective, conscious and objective knowledge. From a corporate perspective, Shoenherr *et al.* (2014) believe that explicit knowledge may only permit competitive advantage to a small degree, as the knowledge is easily transferrable to competitors and may be imitated with modest effort. Consequently, tacit knowledge is more valuable as it is difficult to reproduce by an external organisation, yielding competitive differentiation (Schoenherr, et al., 2014). Although Polanyi’s theory remains widely accepted (Nonaka & Takeuchi, 1995; Khuzaimah & Hassan, 2012; Castellani, et al., 2019; Hampl, 2020), not all scholars agree with Polyani’s dichotomy of tacit and explicit knowledge. There is increasing support (Botha, et al., 2014; Nguyen, et al., 2015; Zaim, et al., 2015; van der Hoorn & Whitty, 2019) for the theory proposed by Jasimuddin *et al.* (2005), where knowledge is not categorised in to tacit and explicit, rather it is a spectrum between the two extremes of tacit and explicit, with knowledge containing a blend of both. Nonaka and Takeuchi (1995), however, hold that Polanyi’s distinction between tacit and explicit knowledge is valid, with the authors recognising that the interaction of tacit and explicit knowledge is central to the foundation of knowledge management.

Knowledge management is a critical organisational resource and managing it strategically can enable proprietary competitive advantage (Roy, et al., 2012). A number of theories have been developed in an effort to explain how organisations can leverage the knowledge of their employees by sharing, generating, evaluating and combining their knowledge and learn from them (Argote, 2013). One of the better-known theories of organisational learning is Nonaka’s (1991) SECI model. This paradigm highlights four patterns of knowledge creation in organisations, through socialisation, externalisation, combination and internalisation (SECI). The SECI model contains three main elements: 1. four modes of knowledge conversion between explicit and tacit; 2. a shared context called ‘Ba’, and 3. knowledge assets (Sarirete & Chikh, 2010).

Socialisation is the condition where tacit to tacit knowledge transfer occurs from one individual to another, such as novices learning from an expert’s experience (Allal-Cherif & Makhlouf, 2016) and can take the form of nonverbal communication (Houston, 2019). Externalisation involves the codification of an individual’s knowledge, making it accessible for others, turning tacit knowledge into explicit (Kazi, 2005). Combination is said to have occurred when explicit knowledge is gathered and processed to produce new knowledge, known as an explicit to explicit transfer (Sarirete & Chikh, 2010). Internalisation is said to have taken place when a person takes explicit knowledge and transfers it to tacit knowledge, such as when the introduction of new work practices becomes inherent part of performing a task (Winanti, et al., 2020).

‘Ba’ is defined as the shared area or context in which knowledge is created, shared and used and where the four models of conversion occur, and can be physical, virtual or mental (Tyagi, et al., 2015). Finally, the ‘knowledge assets’ are the intangible firm-specific resources, such as the inputs or outputs of the knowledge creation process, that may be utilised to yield value (Tyagi, et al., 2015). Nonaka *et al.* (2000), in order to understand how knowledge assets are created, acquired and exploited, categorised knowledge assets into four types: experiential, conceptual, systemic and routine. Experiential knowledge assets consist of tacit, hands-on experience, skills and know-how acquired through shared practice, dialogue and discussion, which are difficult to replicate, providing a firm with a competitive advantage (Nonaka, et al., 2000). Conceptual knowledge assets are explicit knowledge and are comprised of images, symbols and language, such as corporate branding, and exist in the minds of clients and employees as their perception of the firm. Systematic knowledge is explicit knowledge, codified and stored in documents, specifications and databases (Sarirete & Chikh, 2010). Routine knowledge assets are tacit knowledge that is embedded in the routine day-to-day running of an organisation, characterised by being ‘practical’ (Nonaka, et al., 2000).

The SECI model is not without its’ critics, as highlighted by Martin and Root (2009) and Tammets (2012), who find Gourlay (2003; 2006a; 2006b; Gourlay & Nurse, 2005) as a sharp detractor of Nonaka’s SECI model. Much of Gourlay’s criticism is levied at Nonaka’s treatment of tacit knowledge and that the model is vague and over-complicated (Sarayreh, et al., 2012). Other critics believe that the SECI model has limited applications due to cultural differences (Tyagi, et al., 2015; Talaskou &

Belhcen, 2019), whilst recent criticism focuses on the subjective nature of Nonaka's understanding of knowledge, claiming that the model is now inadequate due to radically improved communication methods (Sarayreh, et al., 2012). Nonaka and von Krogh (2009) responded to the criticism by confirming the distinction and interaction of explicit and tacit knowledge in terms of organisational knowledge. Martin and Root (2009) found that the critics of the SECI model are 'limited in numbers' and 'largely based on misinterpretations of Nonaka's work', concluding that the SECI model is suitable for use in construction management. The SECI model's strength lies in the conversion of knowledge, which is suited to construction's project-based typology (Martin & Root, 2009).

3.5.2 Capturing Knowledge

Construction is a knowledge-based industry (Kazi, 2005; Egbu & Robinson, 2007), with four characteristic types of knowledge identified, including know-what (the accumulation of facts), know-why (scientific knowledge), know-how (skills or capabilities) and know-who (information on who knows what) (Egbu & Robinson, 2007). Most companies recognise the criticality of information and knowledge and strive to implement processes to manage it, with organisational learning described by some as the Holy Grail of successful business (Rupčić, 2020).

The industry faces two significant challenges with regard to learning and the management of knowledge, the first being the fragmented nature of the industry (Houston, 2019), where there is a diverse range of stakeholders with specialisations and expertise across many locations (Schröpfer, et al., 2017), complicated through the existence of professional silos, with their own knowledge and language. The second challenge is the temporal project-oriented nature of construction, with multidisciplinary project teams, thought of as a 'multidisciplinary organisation' (Dave & Koskela, 2009), having a limited life span (Vrijhoef & Koskela, 2005), and on termination of a project, the team members are disbanded to engage with new projects and new teams with subsequent knowledge loss (Shokri-Ghasabeh & Chileshe, 2014). The end of a project is also the end of collective learning and gives rise to the 'project amnesia' phenomenon, where project insights are not retained by the organisation (Schindler & Eppler, 2003). Project amnesia is a problem for project-based organisations and, according to Schindler and Eppler (2003), it is evident when the knowledge is required again to solve similar problems in similar projects, it is difficult to retrieve and inevitably mistakes are repeated. Succinctly, knowledge is largely lost at the end of projects (Eken, et al., 2020). There were four categories of reasons proposed by Schindler and Eppler (2003) for project amnesia, as follows:

i. Time pressures exist towards the end of a project to complete it and commence the next project
ii. Motivation of staff to record lessons learned, such as ‘wrong modesty’ of those possessing knowledge or a fear of sanctions for mistakes made
iii. Discipline can be lacking in following procedures and methods to record lessons learned. Team members sometimes do not see a benefit in sharing their knowledge.
iv. Skills may be lacking in team members’ ability to coordinate meetings and elucidate knowledge from the minds of the knowledge holders.

Mansourian and Vallauri (2020) agree with the four reasons provided by Schindler and Eppler (2003), although they believe that the lack of a learning culture within an organisation is also a distinct cause of project amnesia.

Bakar *et al.* (2016) established a positive correlation between construction companies developing their knowledge management capabilities and growth, profitability and commercial success in terms of turnover and employment. Other writers were more direct, stressing that learning must be guided and integrated into the systems, practices and structures of an organisation to be shared to enable a change in performance (Antunes & Pinheiro, 2020). Balthazard and Cooke (2004) emphasised that knowledge management yields competitive advantage through recognising employees’ tacit knowledge and converting it to explicit knowledge, echoing the SECI concept, which may then be shared across an organisation. Kaklauskas *et al.* (2013) presented a list of tacit knowledge in the construction project management context, encompassing expertise, understanding, skills, professional intuition, competence, experience, organizational culture, informal organizational communication networks, intellectual capital of an organization, ideals, traditions, values, and emotions. Bakar *et al.* provided a succinct summary of tacit knowledge in construction as ‘experience and expertise available in the mind of the construction professional, the company culture, from lessons learned and know-how’ (Bakar, et al., 2016). The benefits of past experiences may be maximised by learning from both success and failure through capturing, disseminating and applying lessons learned (Duffield & Whitty, 2016).

Construction organisations are encouraged to accumulate knowledge through the use of BIM, IT systems and visually-based techniques such as 3D photography, video recording and time-lapse photography (Jepson, et al., 2019). To enhance the effectiveness of inter-project knowledge transfer, research conducted on knowledge transfer within construction companies by Ren *et al.* (2018) recommended four components:

1. Standardise project management, as this will overcome the temporal nature of projects by creating similarity between projects.
2. Promote informatisation of projects, where IT is conducive to the acquisition, storage and dissemination of knowledge
3. Establish a post-project evaluation system, which will overcome the urgency to disband the project team and commence a new project
4. Create a shared culture, as this will stimulate behaviour and an intention to transfer knowledge, particularly as it does not usually occur spontaneously

This view broadly aligns with that of Akhavan and Zahedi (2014) who described a process for successful knowledge transmission:

> *'…establish a knowledge strategy with a suitable knowledge structure and education scheme to inspire knowledge sharing among employees, a positive organisational culture which includes rewards and incentives for knowledge sharing, with IT providing advanced tools for the collection of knowledge data.'*

Omotayo (2015), in an effort to describe the means to effectively manage knowledge, proposed a requirement for three components – people, process and technology, which is similar to the steps required to create a knowledge management system as described by Ochieng (2018), that is, people, practices and technology. Robinson (2005) recognised that IT is essential for the creation of knowledge management systems where it can be used to capture, codify and make intelligent decisions on collected explicit knowledge, whilst providing communication and recording capabilities when tacit knowledge is being transferred, such as during post-project reviews or brainstorming.

There have been several knowledge management systems and tools developed over the past 20 years in both academia and industry, based on technological platforms or infrastructure designed to facilitate knowledge sharing and aid the knowledge transfer process (Liu, et al., 2019). Some examples of construction knowledge management systems include KLICON, C-SanD, CLEVER, COLA, Capri.net, CAPRIKON, OSAKMS, CBIMKM, ICKMS. Knowledge Learning in Construction, or KLICON, is a mechanism for capturing knowledge from design concept through to detailed design, to permit contractor understanding at tender stage (McCarthy, et al., 2000) and focusses mainly on the use of IT to capture knowledge. C-SanD is a project designed to develop organisational practices to create knowledge and encourage sustainable development (Khalfan, et al., 2003). CLEVER (Kamara, et al., 2003) was a project which focussed on the development of a transfer of knowledge framework in a multi-project environment in construction. Cross Organisational Learning Approach (COLA), to facilitates the capture and creation of knowledge (Kazi, 2005), achieved through learning-orientated reviews. CAPRIKON (Tan, et al., 2006) is a joint university/industry research project based on the Capri.net project (Tan, et al., 2012) into the Capture and Reuse of Knowledge in Construction, with the objective of establishing a model for the live capture of reusable information in construction projects. OASKMS (Chong, et al., 2007) is an open application sharing knowledge management system developed for the Vassa City Construction Department in Finland. CBIMKM (Lin, 2014) is a Construction BIM-based Knowledge Management system for general contractors, enabling collection of knowledge through the BIM design environment. ICKMS (Liu, et al., 2019) is an Integrated Change and Knowledge Management System designed to capture and manage both change and knowledge through a unified platform.

Organisational culture can be a significant impediment to knowledge transfer, highlighted as the underlying reason for most knowledge management failures (Shokri-Ghasabeh & Chileshe, 2014), where harsh organisational climate, absence of trust and lack of supervisor support restrict knowledge acquisition (Ren, et al., 2018). Furthermore, as most knowledge in construction is tacit, based on experience and passed down from mentor to mentee rather than codified standards, procedures or manuals, it will be lost if the employee relocates, resigns or retires (Bakar, et al., 2016).

Transferring knowledge within, between and across projects faces challenges in practice, due mainly to the organisation’s culture, particularly the subtle dynamics through which cultural elements contribute to knowledge transfer (Wei & Miraglia, 2017). Construction is known to lag behind other industries in adopting IT, restricting the opportunity to exploit knowledge management applications (Okere, 2017). Ren *et al.* (2018) concur, identifying IT as a critical influencing factors on knowledge transfer, in addition to the geographical distance between projects, the similarity of projects, the urgency to transfer knowledge and the temporality of projects. Jepson *et al.* (2019) highlighted barriers to knowledge transfer found in the archaic technologies and systems in use, where available technology has not been harnessed to capture knowledge. This has been recognised by McCarthy *et al.* (2000), where the authors suggest that as IT develops, efficiency, quality and the use of organisational knowledge will also increase. Although some companies are aware that leveraging organisational knowledge will create competitive advantage, they remain unsure how to capture the knowledge, because there is difficulty in identifying a suitable system as there are numerous available (Okere, 2017).

3.6 Addressing the Knowledge Gap

It was demonstrated in a review of current practice that the planning and scheduling of construction projects, including reinforced concrete (RC) frame schemes, relies on knowledge of past performance, with historical production outputs informing decisions on task durations. However, there are discrepancies in the duration of planned and achieved progress in construction projects and it is suggested by some academics that inaccurate estimates of time in construction schedules can lead to project failure, as outlined above. The inaccuracies are rooted in the psychological bias of planners and the planning fallacy, where tasks are estimated to take less time than they actually require. Human’s fallible memory and incorrect evaluation of past experiences feeds into the planning fallacy, however it has also been shown that it can be avoided. A number of studies found that mentally unpacking tasks may increase or decrease task duration estimates, leading to under or overestimation, with a deeper conceptual link between probability judgement and duration estimation. Notwithstanding the task unpacking solution, RCF, where a statistical evaluation is made based on historical performance data, is proposed by academics as the optimal solution, endorsed internationally by both industry and state bodies.

Therefore, key to solving the issue of inaccurate construction schedules is to collect performance data and information on the productivity achieved at the construction phase, which places knowledge management in a central position to the enhancement of schedule accuracy. It was found in a review of the literature that a temporal nature and extensive fragmentation yields a significantly complex project-based industry (Dave & Koskela, 2009), and in the absence of implemented knowledge management techniques, organisations are in danger of repeating past mistakes and not capitalising on the knowledge available, missing the opportunity to develop a competitive advantage.

3.7 Summary

This chapter has reviewed the extant literature surrounding the issue of scheduling in construction to develop a theoretical foundation to the practice-based problem previously identified in Chapter 1. Following the definition of project management and a review of the inaccuracy of construction scheduling, the social science of performing planning and scheduling decisions was discussed. Knowledge management and explicit and tacit knowledge were then examined, finding that data can stored, analysed and managed through a knowledge management system.

According to Liu *et al.* (2015), knowledge transfer between team members may be facilitated by IT solutions, and whilst the application of IT is a crucial aspect of project management there are more than 100 project management programs in the Architecture, Engineering and Construction (AEC) industry. All of these programs provide central data repositories for data sharing, information exchange and communication in a construction project, however, the vast array of choice is a barrier to making an informed selection.

A change in work practices has the potential to enhance decision-making and reduce project risk, with more open collaboration facilitated through the sharing of project progress achievements, both past and current, between all stakeholders. This change in work practice would need to be justified prior to becoming a strategic offering, as it also has the potential to expose confidential information to competitors in the sector.

The following chapter considers the current practice as identified in Chapter 2, and the examination of the current literature in this chapter, and proposes a method to collect productivity data and create a database to contain and analyse the productivity data.

4 Synthesis and Conceptualisation

4.0 Introduction

The purpose of this chapter is to draw together Chapters 2 and 3, establishing a strategy to achieve a solution to the research question highlighted in Section 1.3. To answer the research question, and provide a basis on which to develop the research methodology and data collection methods, there are a number of components which must be considered. Firstly, the development of a knowledge management system will be investigated, followed by a review of traditional and contemporary performance data collection methods. Then, productivity in RC frames will be explored, where the rationale for calculating a productivity baseline rather than a productivity benchmark is established. Next, Flyvbjerg's (2018) five-step method of RCF is presented, where novel formulae for the calculation of the reference class forecast are created and compiled in a format suitable for inclusion into a data analysis process. Finally, the conceptual framework is presented, indicating how the research will build on the problem in practice and current academic views to create a database which includes an automated reference class calculation.

4.1 Developing a Knowledge Management System

As outlined in Section 1.3 above, the aim of this thesis is to produce a novel tool to enhance construction project management by improving construction schedule accuracy in reinforced concrete (RC) frame buildings. In Chapter 2 it was found that the challenge for planners is to identify accurate levels of productivity achieved on site and use this data and information to forecast new construction schedule durations. The collection and analysis of productivity data will permit more accurate duration calculations as it provides an insight into what has historically been achieved within an organisation (Flyvbjerg, et al., 2018). In an attempt to understand the true daily production rates for formwork erection achieved by carpenters, the quantity of reinforcement fixed in position by steel fixers, the duration for one slab cycle, and how this data and information can inform decision making, the research question identified in Section 1.3 above has been developed.

Chapter 2 identified that progress can be measured in a number of ways, the changing time intervals, and the different people involved. In response to this condition, the frequency of progress measurement must be evaluated, with the optimum time interval for progress measurement established. Furthermore, the data required to measure progress in RC frame construction was identified in Section

2.2.4, as well as the means to assess progress. An understanding of the influence RC frame tasks exerts on scheduling decisions, including the perception planners have regarding the relative importance of tasks, is also required. It is anticipated that addressing these uncertainties will prove beneficial to the planning of future projects, enabling the harmonisation of output values across the planning, estimating and project management functions, enhancing project schedule accuracy and permit greater project control. In order to facilitate the harmonised condition and address the current divergence between the planned and actual production outputs, a rigorous method to measure and record progress is therefore required, followed by the storing, analyses and dissemination of the production data. This view is supported by Akanmu and Anumba (2015), where they recommended that progress information is continuously collected and used to inform and improve the planning phase of construction, with a generalised BIM model compiled using the harvested information. Further research by Haobo (2018) found that the construction schedule duration could be determined from a BIM model of an RC frame structure, using an algorithm which analysed the member type, geometric properties and output rates.

4.1.1 Knowledge Management Strategy

The importance of a knowledge management system to manage harvested data was established through the literature review in Section 3.5.2 above, where several different types of knowledge management systems were identified. Academics such as Jepson *et al*. (2019) noted that knowledge will be lost if it is not collected and shared, recognising that there is a direct correlation between the use of knowledge management systems and positive project outcomes. The knowledge management process has been evaluated by Gunasekera and Chong (2018), who defined it as four continuous activities: knowledge creation, sharing, storage and application. Building on these four requirements, Jepson *et al*. (2019) found that the primary objectives of a knowledge management system are to create repositories, improve knowledge access and transfer, enhance the knowledge environment, and to manage knowledge as an asset.

Liu et al. (2019) developed a set of key features which they believe should be included in a knowledge management system, highlighting the importance during the construction phase of the simultaneous management of changes, dependencies and knowledge, incorporating automated system functionality whilst addressing Gunasekera and Chong's (2018) activities and Jepson *et al*.'s (2019) objectives above. The key features of a knowledge management system identified by Liu et al. (2019) are applied to this research as follows:

i. **Automation of dependency checking**

The proposed tool will require an embedded matrix of interdependencies, where the interrelation of labour and time are defined.

ii. **Tracking of changes by approved users**

It is essential that the data entry and information retrieval functions are protected by password to authorised and trained users to prevent corruption of the database, such as accidental deletion of data.

iii. **Automation of notifications**

Updating the database with new progress data will modify the schedule baseline. Therefore, notifications can be set to inform stakeholders such as the database manager and planners to advise on the addition of data and the modification of the baseline.

iv. **Tracing of change history**

The database requires a record of user changes, which will be enabled through the password protection and the indexing of data entries to individual users.

v. **Capture lessons learned**

The main lessons learned are contained in the analysis of progress and actual schedule position against the predicted, however provision to enter the reason for any construction schedule delays or improvements is required.

To implement a knowledge management strategy, Song and AbouRizk (2008) proposed a framework which requires the productivity measurement, data acquisition and data modelling processes to be defined. They opined that productivity measurement is conceptualised by firstly deciding what data is required, and secondly, understanding what data can be measured consistently. This view is supported by Akanmu and Anumba (2015), where they recommend that progress information is continuously collected and used to inform and improve the planning phase of construction. Data acquisition, according to Song and AbouRizk (2008) is a set of policies, procedures and techniques, with output capture typically performed through a quantity survey, linked to the manually recorded duration to complete the task. The data modelling of productivity is then undertaken using a technique suitable for the quality, nature and type of data (Song & AbouRizk, 2008).

Mapping this research to Song and AbouRizk's (2008) requirements, the productivity measurement criteria have been identified in Section 2.2.3 above, as the formwork and reinforcement output and slab cycle times, with the measurement of area, mass and time straightforward to perform and manage on an ongoing basis. Considering the RC frame workflow identified in Section 2.2.1 above, other input resources are excluded from the assessment due to the labour element generally accounting for more than 50% of the total cost of a concrete structure, in which formwork and reinforcement are the most labour-intensive tasks with the greatest influence on productivity (Pellegrino, et al., 2012). The data acquisition for formwork erection, reinforcement installation and slab cycle time will be through a query form which requires site progress to be entered. The data modelling will then be undertaken using visual basic (VB) script and excel functions, allowing retrieval of data through a further VB query form.

4.1.2 Analysing Data

The process of digital capture and storage is known as digitisation (Madanayake & Egbu, 2019) and is taking place within the industry at a slow pace. According to research undertaken by Bilal *et al.* (2016), whilst construction is producing large volumes of heterogenous data, or 'Big Data', it is not yet benefiting from the data and is yet to fully adopt Big Data analytics to the same degree as other industries. Big Data is described in terms of the 3V's: volume, variety and velocity, (Bilal, et al., 2016), however some writers include veracity and value (Shastri & Deshpande, 2020). Shastri and Deshpande (2020) offer the following explanation of the 5V's:

1. Volume relates to the quantity of data;
2. Velocity is the flow rate of the data;
3. Variety is the blended nature of the data;
4. Veracity refers to the quality of the data used for analyses; and
5. Value is the intrinsic value of the data.

Ghasemaghaei *et al.* (2018) found that the majority of organisations could not take advantage of their initiatives to manipulate big data due to a variety of reasons, such as poor quality data, inappropriate analysis and a lack of analytical skills. Indeed, Madanayake and Egbu (2019) hold that performance prediction based on collected data is one of the greatest opportunities within the grasp of construction industries. This research addresses the challenges of utilising big data through the development of a tool which collects, stores, and analyses data, presenting the resulting information for use. It is proposed in this research to gather progress data, analyse it and process it using the typical scheduling methods employed by planners.

Goh (2005) recommended that organisations harness technologies to manage knowledge collection and sharing systems. To this end, Kofler (2003) promotes Microsoft Excel software as a database for a number of reasons, such as familiarity, ease of use, availability of the software, inherent database functions including Visual Basic programming interoperability, and the suitability of Excel files for data exchange throughout an organisation and between organisations. A further benefit is that Excel has the capabilities to read data exported from BIM modelling schedules such as Revit or ArchiCAD, and can read data from CSV files from scheduling software programs such as Power Project or Primavera in addition to data directly from Microsoft Project. It is therefore considered appropriate that the database is constructed in Excel and VB and the data analysed therein, although it is recognised that this research does not capture or take advantage of Big Data in the way that many data practitioners may consider appropriate analysis or 'deep diving' into the data, where the volumes of data are smaller and not analysed to the extent that may be possible. The development of the code to manipulate progress data and provide valuable productivity insights for scheduling is detailed in Section 9.1 below.

4.2 Collection of Production Data

Section 3.5.2 highlighted the requirement for a knowledge management system to capture internal project data, which includes details of the progress and performance achieved. Knowledge management, according to Robinson *et al.* (2005), is the unlocking and leveraging of different types of knowledge so it becomes an organisational asset. Payne (2014) believes that knowledge itself cannot be managed, it is the environment in which knowledge is created and shared that can be managed, through the use of processes and tools. Knowledge management tools are categorised into four types comprising, according to Patel *et al.* (2000), of the following:

- knowledge generation
- knowledge representation
- knowledge retrieval, and
- knowledge sharing

However, Eken *et al.* (2020) do not agree and blended these four types into a single model, proposing a 'lessons learned' management process for project-based construction companies. Their model was informed by a number of needs, where the required data was identified, collected, processed and retrieved for use through userinterfaces, demonstrating the feasibility of a combined knowledge management model, as illustrated in Figure 4.1.

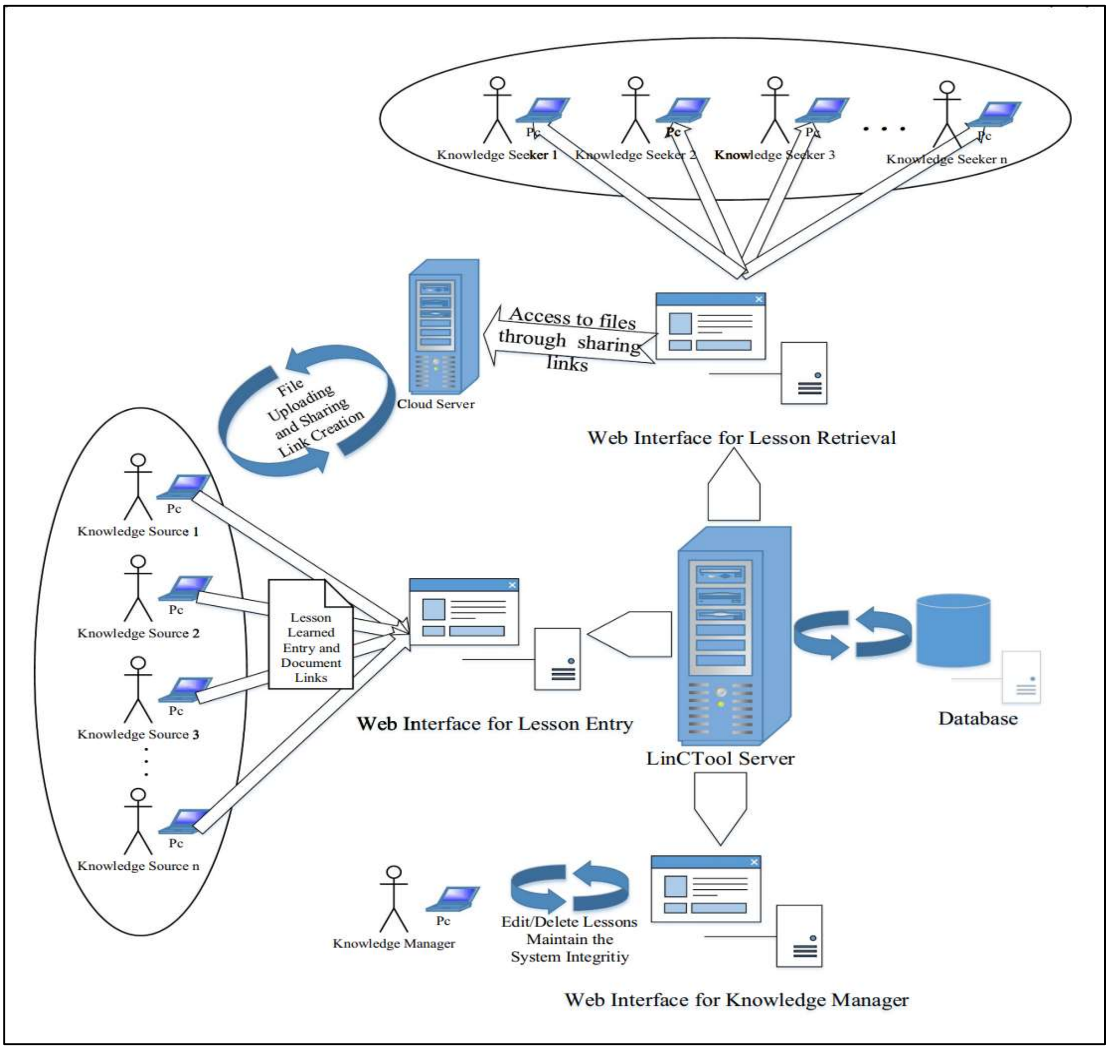


Figure 4-1. Knowledge capture and sharing (Eken, et al., 2020)

The reference class forecast methodology, identified previously and further developed in Section 4.4 below, requires data to be collected in an ongoing process on which to base the forecast. Park *et al.* (2005) note that production measurement is not a 'one-time task' and should be undertaken continuously, applying a standardised data collection system to provide reliable and consistent results. In the current process, as-built data is collected from site and the construction schedule software is updated to determine the current position against the schedule, as outlined in Section 2.2.4 above. The collection of the data may be performed in a number of different ways, including visual inspections, physical measurements, or a combination of these traditional methods.

4.2.1 Traditional Performance Data Collection

Notwithstanding the importance of project control, the traditional manual methods of progress measurement remain prevalent despite being labour intensive (Navon & Haskaya, 2006) and undertaken through visual inspections and building surveying methods (Zavadskas, et al., 2014).

Visual inspections have been criticised by Zavadskas *et al.* (2014) as traditional progress assessment methods involve human judgement, are expensive and occur infrequently. Some researchers, such as Kopsida *et al.* (2015) are critical of the subjective nature of the measurement of percentage completion, as discussed previously in Section 2.2.4 above. One of the main drawbacks of assessing progress through visual inspections is that it is generated irregularly and infrequently and the resulting data has low quality, low integrity and is prone to error (Navon, 2007; Rebolj, et al., 2008).

There have been some advances in simplifying the collection of data, for example Dave et al. (2016) recommend the use of a dedicated smartphone interface to log data, however, this will only assist in the recording and manipulation of the data gathered at the work site, which remains estimation-based. Alizadehsalehi and Yitmen (2019) hold that most construction companies worldwide do not use automated progress monitoring technologies, relying on manual inspections for their project control data. Furthermore, Isaac and Navon (2014) found that whilst there are advances in the automation of progress monitoring, the requirement remains to include a degree of manually collected site data.

Physical measurements, or geospatial measurement methods include the acquisition of data through total station GIS and GPS measurements as discussed by Omar and Nehdi (2016). These techniques are performed using the geographical information system (GIS) or global positioning system (GPS) capabilities of standard surveying equipment, such as the total station, used by the site engineer to measure distance and determine location using local or national coordinates.

The process may be semi-automated through the use of modern robotic total stations, where the instrument is scheduled to survey pre-determined targets or a specified zone (Liang, et al., 2011). This type of GIS temporal monitoring is considered beneficial by many, such as Buell (2008), Petrov et al. (2015), Luo et al. (2016) and Omar and Nehdi (2016), although Petrov et al. (2015) recommend that it is enhanced with other forms of data. This view is also supported in studies by Wagner (2016) and Liang et al. (2011), where they indicate that GIS for construction progress monitoring is most suitable when utilised in conjunction with other methods.

4.2.2 Automated Performance Data Collection

There are also a number of innovative automated data collection technologies available to capture project progress in real-time, such as laser scanning, photogrammetry and cyber physical systems, incorporating automated project progress updating of the construction schedule through the BIM model (Omar & Nehdi, 2016).

Laser scanning, sometimes referred to as LADAR (Laser Detection and Ranging) involves optical instruments scanning the desired area with a greater degree of accuracy and detail than a total station (Bosché, et al., 2015). The use of laser scanning to monitor construction progress has been the subject of a number of studies, such as Gao *et al.* (2012), Zhang *et al.* (2016) and Omar & Nehdi (2016). It is recommended by some researchers that laser scanning is most advantageous when used in conjunction with other methods of measurement such as photogrammetry and GIS methods (Kiziltas, et al., 2008; Han, et al., 2015). A principal benefit of laser scanning is the speed of large-scale point collection and the accuracy achieved (El-Omari & Moselhi, 2008), although the accuracy has been called into question with some (Zhang & Arditi, 2013; Golparvar-Fard, et al., 2011) finding inaccuracies regularly occur in the data. Laser scanning is very accurate for production data capture, although the scans frequently require significant amount processing and ‘noise cleaning’ to remove unintentionally read points, such as wildlife or traffic.

Photogrammetry is a process involves a series of photographs or video taken of the work area, with software then used to analyse the images and compare them with the previous condition, the difference being interpreted as the progress achieved (Dai & Peng, 2013; Zhang & Arditi, 2013). Photogrammetry can yield accurate results at a relatively low cost, but it relies heavily on favourable environmental conditions (Klein, et al., 2011), such as achieving satisfactory visibility in strong or weak light, in conditions of high levels of dust or vibration, inclement weather (such as fog, rain or snow) and surface reflectivity, which affect the integrity of the results (Hamledari, et al., 2017). To address these concerns, Han and Golparvar-Fard (2015) and Kim et al. (2013) proposed that construction sequencing could be utilised to make inferences on elements that are completed but not visible.

Cyber-physical systems, or CPS, are used as an interaction between the virtual world and the physical world, with both interacting seamlessly through computation and networking (Yuan, et al., 2015; Chih-Che, et al., 2016). In a built environment setting, this allows coordination between the physical elements and the virtual models, with data collected by embedded computer sensors and networks and transmitted automatically, permitting monitoring and control of the physical processes (Derler, et al., 2012), facilitating integration between BIM and the physical construction (Akanmu, et al., 2012). Chi, Hampson and Biggs (2012) undertook initial research into how CPS could be integrated with the temporary works used to construct buildings, later extended by Yuan, Anumba and Parfitt (2016), whilst Akanmu and Anumba (2015) found that the introduction of sensors or other forms of embedded instrumentation would enable the monitoring of resources and activities in the live construction phase.

4.2.3 BIM and Performance Data Collection

Bilal *et al.* (2016) highlighted the benefit of using BIM to capture data, supported through collaboration amongst stakeholders in a multidisciplinary environment. Akanmu *et al.* (2012) recognise the benefit of integrating the virtual BIM model and data collected on the constructed physical condition, a recommendation supported by Akanmu and Anumba's (2015) argument that the BIM model is populated using information gathered during the construction phase. This will allow development of the 4D BIM model, containing information on the planned and achieved progress. Kim et al. (2013) found that it is possible to automate the construction progress measurement and schedule updating through the use of remote sensing technology and 4D BIM. Kim *et al.*'s (2013) research proposed that 3D data could be enhanced through the inclusion of a linked schedule, effectively creating a 4D BIM model, which is then populated with data measured by laser scanning.

The technique has been improved through automating the process of removing inconsistencies and occluded elements from the data set. It is apparent that one of the difficulties in integrating data from automated site progress measurement, in particular laser scans, video images and photographs, is the occurrence of partial information, or in some cases superfluous information. Although image collection is a positive development, the difficulties identified with vision-based detection persist, where some components obscure others and the environmental and atmospheric conditions can influence the quality of data obtained. Notwithstanding the difficulties in accessing a complete data set, any additional information is valuable, although research is ongoing to improve data collection. In the case of Kim *et al.* (2013), they suggest that the missing information is extrapolated through inferences form the schedule sequence.

Matthews et al. (2015) devised a performance measurement algorithm, recommending that progress is tracked on site, informing the BIM model of progress automatically. This was performed with a view to analysing and subsequently improving performance and productivity. The identification of disruptions to the schedule permit interventions and allow the client, design and production teams to prioritise other project activities (Hu, *et al.,* 2016). This can only occur if the progress is monitored, and rectification actions will occur sooner and more efficiently if the progress is monitored automatically and difficulties addressed in a collaborative, cooperative working environment.

Alternative methods of collecting progress data include to remotely monitor the installation of the carpenter's formwork, which was found to be accurate and unobtrusive. Some work has been done on this in the past, including photogrammetry and laser scanning (Zhang, et al., 2008) as described above.

There have also been developments in the use of cloud-based project management tools for recording progress in the field. For example, cloud applications such as PlanGrid, Site Progress Mobile and PlanRadar collect data on site and update the schedule with relative ease. The progress can then be entered into the BIM model to maintain an up-to-date 4D BIM as-constructed model.

4.2.4 Performance Data Collection Methods in Practice

Whilst there are a number of competing automated methods to assess progress, these remain in their infancy and are yet to be fully embraced by the construction industry. Laser scanning, photogrammetry and CPS provide high-volumes of accurate data, although it is uncommon to use these methods as they are seen as time-consuming and costly in an era of tightening profit margins. From industry experience, organisations prefer to follow rather than lead, finding comfort and surety in the current processes, even though these processes produce variable results.

4.3 Baseline Productivity of RC Frames

It was found in Chapter 2 that true production rates are generally not known when planners are developing construction schedules, and when they are known, uncertainty persists regarding their accuracy. Consequently, there is a clear requirement to evaluate the production rates relating to formwork erection and reinforcement installation to assist in the scheduling function, particularly as Section 2.2 above shows these are normally critical path activities. Productivity will also be enhanced through more accurate scheduling, as Loosemore (2014) has indicated that poor productivity is also linked to a lack of detailed planning and scheduling. Naoum (2016) expanded on this point, stating that productivity is directly linked to ineffective planning particularly at the pre-construction stage, but also due to the planning undertaken during the construction phase.

Productivity is defined as the ratio between an output value and an input value used to produce the output (Pornthepkasemsant & Charoenpornpattana, 2019). In the construction industry, productivity can be divided into two measures: (1) the total factor productivity (TFP) which takes all outputs and inputs into consideration; and (2) partial factor productivity (PFP), where outputs and a single or specific set of inputs are considered (Jarkas & Horner, 2015). TFP includes input resources such as labour, plant and materials, and accounts for all inputs, tangible and intangible, including, according to Loosemore (2014), management practices and work environments. However, with this expression of productivity it is difficult to accurately measure all of the input resources and consequently is often seen as unreliable (Loosemore, 2014). In contrast, the PFP includes capital productivity, labour productivity or plant and equipment productivity. Jarkas and Horner (2015) provide the following PFP equation for labour:

$$Labour\ productivity = \frac{Output\ Quantity}{Effort}$$ *Equation 4-1*

This provided the basis for *Equation 2-1* and *Equation 2-2* for formwork carpenter output and steel fixer output respectively, as identified in Chapter 2. The time element ('person-hours' of effort) of the above equation for labour productivity is prone to subjective interpretation, as according to Jarkas and Horner (2015), there are a number of different interpretations of 'time' possible when considering construction schedules: (1) total time; (2) available time; and (3) productive time. The total time is the total paid time, and is most frequently used in estimating costs. The available time is the total time, less delays which are unavoidable, such as paid breaks, training and inclement weather. Productive time is the time spent involved in undertaking a task and is expressed as the available time less avoidable delays such as delays arising from inefficient site practices (Jarkas & Horner, 2015). To allow comparable productivity baselines and key performance indicators (KPI's), in this research, the concept of 'time' with regard to productivity is taken as the total time. It has also been identified that labour has a significant influence on project productivity and consequently schedule progress, whilst materials and equipment have less impact (Jang, et al., 2011).

The development of baseline productivity has been defined through a number of methods by academics, with some disagreeing on what baseline productivity means. Lin and Huang (2010) wrote that baseline productivity has two meanings, that is, it can be the best possible performance achievable on a project, or a measure of typical operating performance. Jarkas and Horner (2015) offer a clear delineation between the two terms, identifying a benchmark as a level of performance an organisation might aspire to, whereas a baseline is the normal or standard level of performance an organisation should expect to produce.

Different methodologies to determine baselines and benchmarks have evolved, including the measured mile (Zink, 1986; Zhao & Dungan, 2019) and Thomas's Baseline Productivity Method (Thomas & Zavrski, 1999). Gulezian and Samelian (2003) developed a procedure using control charts to determine the baseline productivity and Ibbs and Liu (2005) proposed an Enhanced Baseline Method using K-means clustering technique, whilst Lin and Huang (2010) promote a data envelopment analysis as an alternative to the measured mile. Zhao and Dungan (2014) developed a baseline using a method based on the control chart process.

The measured mile method is used to evaluate typical productivity, often in situations where lost productivity is of concern and is a comparison drawn between the period under review and another similar, unimpacted, uninterrupted period to yield the baseline productivity (Ibbs & Liu, 2005). Gulezian and Samelian's (2003) were critical of the assessment process with the measured mile as it can smooth variations and omit outliers. Ibbs and Liu (2011) who questioned the measured mile with regard to the objectivity in identifying a similar unimpacted period and noted that daily output can vary due to labour levels as well as productivity. Some academics have also noted that pervasive delays may impact the entire schedule, including the measured mile reference period (Ibbs & Liu, 2005).

Thomas's Baseline Productivity Method (Thomas & Zavrski, 1999) calculated the baseline through a formula which takes 10% of the total workdays and finds the maximum productivity on the construction schedule for this duration. Abdel-Razek *et al.* (2007) support Thomas's Baseline Productivity Method, demonstrating that it has the capability to identify the best and worst performing projects, however, they do not address the main criticism of this process, that is, the figure of 10% of the schedule is arbitrary and may not give a suitable reflection of the overall productivity (Golnaraghi, et al., 2018). Gulezian and Samelian's (2003) method uses control charts and the arithmetic mean of the production rate to determine a baseline value. The control charts consist of data points of daily productivity with upper and lower control limits, with data points outside the limits of the control chart identifying disruption to the production rate.

Ibbs and Liu (2011) enhanced the measured mile analyses through a statistical regression method called *K*-means clustering. In this process, similar clusters of project data are used for productivity comparison in an effort to overcome the difficulties in finding a similar unimpacted period as required for the measured mile analysis. However, the methodology requires a complicated calculation process and, in addition, the *K*-means clustering can yield flawed results, according to Golnaraghi *et al.* (2018), depending on the initial cluster centroid choice.

Data envelopment analysis (DEA) has been used to derive baseline productivity and uses a 'frontier' at the performance peaks which is taken as the baseline of productivity (Lin & Huang, 2010). Xue *et al.* (2008) also used a DEA approach, augmented by the Malmquist Index, which is a statistical method to determine the difference between two productivity frontiers. Zhao and Dungan (2014) disagreed with taking the arithmetic mean of the productivity as with Gulezian and Samelian's (2003) method, because it does not fully take extreme productivities into consideration. Zhao and Dungan (2014) proposed that the data is separated into two groups, 'good productivity' and 'bad productivity' and outliers are eliminated in a procedure similar to Gulezian and Samelian's (2003) control chart method to establish the baseline productivity value.

Alternative Method

The most prominent method of baseline productivity calculation is the measured mile, accepted by UK courts of law and at arbitration (Society of Construction Law, 2017) and whilst there have been various improvements to smooth the calculation, outlying productivity data points are either eliminated or not permitted to influence the baseline calculation. The DEA calculation includes outlying data points as the frontier is based on maximum values, however, these maximum values provide an upper boundary as benchmark values. Using the DEA frontier method will lead to anchoring (Lovallo & Kahneman, 2003), where the most successful projects are used as a benchmark, rather than the most likely, which is one of the main causes of the planning fallacy. Therefore, an alternative method of calculating the most likely productivity rate is required, which will embrace outlying data points, enabling calculation of the task duration with enhanced accuracy. To address this, RCF is presented in the following section as a novel solution to determining productivity rates in RC frame projects.

4.4 Application of Reference Class Forecasting

Defined in Section 3.3, RCF is a method to overcome the planning fallacy of inaccurate forecasting and determine the most likely project outcome. To create a RCF, according to Lovello and Kahneman (2003), Sovacool *et al.* (2014), Sample (2015), Flyvbjerg (2018) and Simon (2020), there are five steps to be undertaken in the process, as shown in Figure 4-2. Reference Class Forecastingbelow.

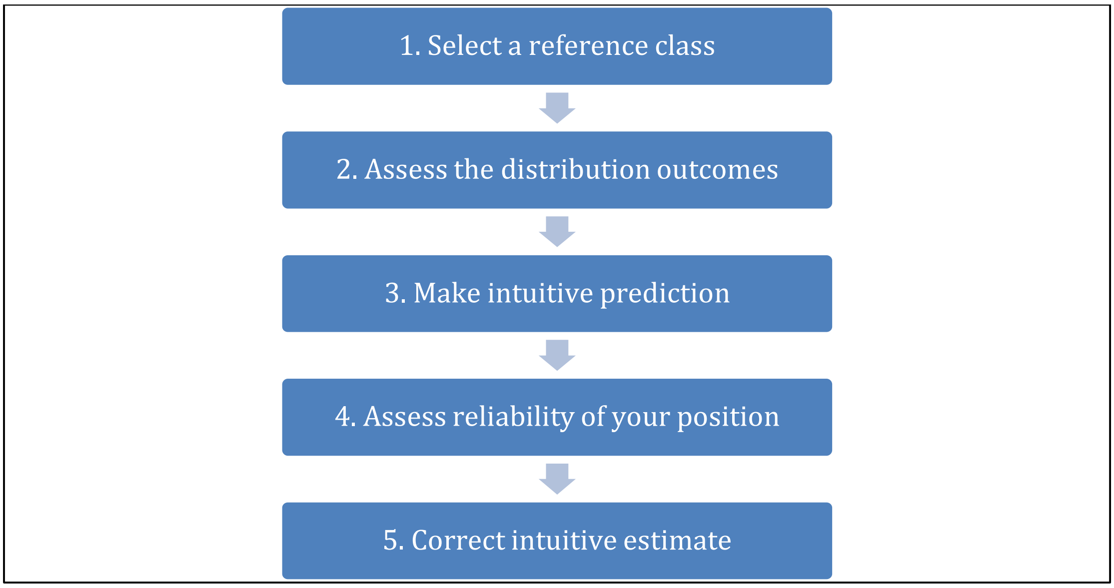


Figure 4-2. Reference Class Forecasting

These steps are now explored in more detail, with specific application to RC frame construction.

1. Select a reference class

According to Fridgeirsson (2016), the main difficulty in choosing a reference class is how the classification is determined, as too narrow a reference class will affect the true level of optimism bias and may omit outlying data. Similarly, if the reference class is too broad, it will encompass projects which are incomparable and provide an inaccurate mean (Fridgeirsson, 2016).

To select a set of reference classes from RC frame projects, it has been established in Section 2.2.1 above that the formwork erection, reinforcement installation and slab cycle times are the critical components and consequently, these are viewed as three different reference classes. It is noted that for the reference classes, they are taken as the entire population of formwork and reinforcement installation durations for flat RC slabs only, it does not include post-tensioned members, beams, dropheads, down-stands, upstands or other slab combinations. Similarly, the slab cycle time reference class is taken as the entire population, whilst the erection of formwork is divided into separate classes depending on the type of formwork system used as the interview results indicated that there was a significant difference in the production rate when using different types of formwork equipment. This is discussed further in Section 8.3 below.

2. **Assess the distribution of outcomes**

A statistical distribution of the reference class chosen in step 1 is then created, with the extremes, median and any clusters noted. The average outcome of the reference class is then calculated, including a measure of variability. It is the standard procedure in the measured mile approach to omit extreme data points which are outside an organisation's normal operating process, according to Zhao and Dungan (2014), and 'eliminate them' from the calculation. Many scholars disagree with this approach, however, (Lovallo & Kahneman, 2003; Taleb, 2010; Flyvbjerg, 2013; Sample, 2015; Awojobi & Jenkins, 2016; Flyvbjerg, et al., 2018) instead recommending that all outlying data points are incorporated into the distribution calculation and none are excluded. Taleb (2010) advocates that the mean absolute deviation (MAD) is used, whilst Khair *et al.* (2017) specifically recommend MAD is used in predicting forecasting errors. This statistical calculation, according to El Amir (2012), is robust and a preferable measure of dispersion as the outliers are taken into consideration:

$$Mean\ Absolute\ Deviation, MAD = \frac{\sum|x_i - \bar{x}|}{n}$$ *Equation 4-2*

Where, x_i is the positive distance of a data point from the median; $\bar{x}$ is the arithmetic mean; n is the number of data points. This calculation gives a mean value which considers the entire population of data points giving an indication of the spread of the values. In terms of reinforced concrete frames, this will be calculated for the achieved outputs for reinforcement and formwork and slab cycle time durations. Taking formwork as an example, the MAD for actual formwork durations is denoted as follows:

$$Formwork\ Mean\ Absolute\ Deviation, MAD_{a_f} = \frac{\sum\left|a_{f_i} - \bar{a}_f\right|}{n_f} \qquad \textit{Equation 4-3}$$

Where a_{f_i} is the positive distance of the actual formwork duration from the median; $\bar{a}_f$ is the median of the actual formwork durations; and n_f is the number of formwork data points in the data set. The MAD method of deviation assessment is preferable to calculating the standard deviation, because the distance of each data point from the arithmetic mean is squared when calculating standard deviation, resulting in larger deviations having an enhanced impact (Leys, et al., 2013). The MAD, on the other hand takes the absolute distance of a point from the median as the deviation and does not square the error (that is, the distance from the mean).

3. Make an initial prediction of your project's position in the distribution

Based on an understanding of the project task in hand, the planner makes an estimation of where it occurs in the distribution and calculates the distance of the estimate from the median absolute deviation. With respect to RC frames, there will be separate estimates for the output of the formwork and reinforcement, and the slab cycle time. The estimated output for slab cycle time is in days, whilst the formwork and reinforcement is measured in m^2 or kg per day, as shown previously in *Equation 2-1* and *Equation 2-2* given in section 2.2.3 above.

4. Assess the reliability of your prediction

The reliability is assessed through estimating the correlation between the forecast and the actual outcome between 0 and 1, where 0 indicates no correlation and 1 indicates complete correlation. The estimate can be based on previous predictions, calculated from the historical predicted outputs and the associated achieved outputs. According to Gorard (2015), the 'traditional' means to measure correlation is to use Pearson's R, which uses covariance, a measure of the degree that two variables are related, and divides it by the product of the sample standard deviations for both variables:

$$Pearson's\ R = \frac{1}{n-1}\sum\left(\frac{x_i - \bar{x}}{S_x}\right)\left(\frac{y_i - \bar{y}}{S_y}\right) \qquad \textit{Equation 4-4}$$

Where the sample standard deviations are given by $S_x = \sqrt{\frac{\sum(x_i-\bar{x})^2}{n}}$ and $S_y = \sqrt{\frac{\sum(y_i-\bar{y})^2}{n}}$.

The standard deviation is a measure of the dispersal of values in a data set, however, it is proposed to use the mean absolute deviation (MAD) in this instance as it is less distorted by large deviations than Pearson's correlation. This is due to the lack of squaring offering more tolerance of non-linearity (Gorard, 2015). The coefficient of correlation, or Modified Pearson's R, may therefore be calculated as follows:

$$R = \frac{1}{n-1}\sum\left(\frac{p_i - \bar{p}}{MAD_p}\right)\left(\frac{a_i - \bar{a}}{MAD_a}\right)$$ *Equation 4-5*

Where: p_i and a_i are the positive distance of the predicted and actual durations from the arithmetic mean; $\bar{p}$ and $\bar{a}$ are the arithmetic means of the predicted and actual outputs; MAD_p and MAD_a are the Mean Absolute Deviations for the predicted and actual outputs. Gorard (2015) proposes that the value of n may be cancelled in the numerator and the denominator and summing the deviations resulting in a more straightforward additive correlation coefficient, RA2, as shown in *Equation 4-6* below:

$$RA2 = \frac{\sum \left| (p_i - \bar{p}) + (a_i - \bar{a}) \right|}{\sum \left| (p_i - \bar{p}) \right| + \sum \left| (a_i - \bar{a}) \right|}$$ *Equation 4-6*

5. **Correct the intuitive estimate**

The intuitive estimate made in step 3 will be biased, most likely optimistically, and is corrected by adjusting the estimate towards the mean, taking into account the intuitive estimate. Kahneman and Tversky (1977) promote regression towards the mean, where the intuitive estimate should be adjusted towards the average for the reference class. Therefore, the regressed output estimate to be used in the creation of the construction schedule forecast, is the sum of the MAD for the achieved durations and the product of the regression correlation and the original estimate less the MAD for the achieved durations, or:

$$O_R = MAD_a + \left[\left(\frac{\sum \left| (p_i - \bar{p}) + (a_i - \bar{a}) \right|}{\sum \left| (p_i - \bar{p}) \right| + \sum \left| (a_i - \bar{a}) \right|}\right).(E_O - MAD_a)\right]$$ *Equation 4-7*

Or, simplified,

$$O_R = MAD_a + [RA2(E_O - MAD_a)]$$ *Equation 4-8*

Where:

O_R = regressed output; E_O = original estimate; $RA2$ = Gorad's regression correlation coefficient; MAD_a = mean absolute deviation of the actual output. *Equation 4-8* is the general equation for schedule forecasting, novel to this research, and may be applied to each component of formwork, reinforcement and concrete.

4.4.1 Developing Construction Schedule Forecasts

Having previously established that RCF is a suitable method for predicting the duration of construction tasks, the process of applying RCF to a data set has been formalised through the introduction of a number of equations as outlined above. The equations have been developed with a view to managing data within a database of RC frame projects, providing the user with task durations calculated from the historic records stored in the database and is further explored in Chapter 9. The conceptual framework is discussed in the following section and will elaborate on the research process and how the knowledge database feeds into the planning algorithm.

4.5 Conceptual Framework

The research problem was highlighted in Chapter 2, identifying how it is manifested in practice and, in order to investigate current planning practice further, historic performance will be analysed encompassing a review of recent construction schedules. The literature review in Chapter 3 examined the underlying reasons for cognitive decision making and the planning fallacy, where planning decisions are biased by optimism as outlined in Section 3.3.4. The writings of leading scholars such as Kahneman, Schön, Taleb and Flyvbjerg have been reviewed in Sections 3.3.4 and 3.3.5 and it was shown that the optimum means to avoid the planning fallacy is to engage in RCF, where reference data from historic performance is used to inform construction schedules.

This research enhances and develops the existing processes outlined in the preceding chapters to propose a tool to enhance the accuracy of construction schedules, incorporating RCF. The current body of literature offers background information on the causes of scheduling inaccuracy and the means to improve these schedules, through the statistical analysis of past performance in the RCF process. The novel aspect of this research Is the application of RCF to RC frame structures in an automated process where the historic productivity rates of trades at task level are monitored and utilised to inform a database, where the data is analysed and retrieved, offering a statistically more accurate forecast for task duration. The conceptual framework is designed to illustrate the research process to achieve this outcome, and is shown in Figure 4-3 below.

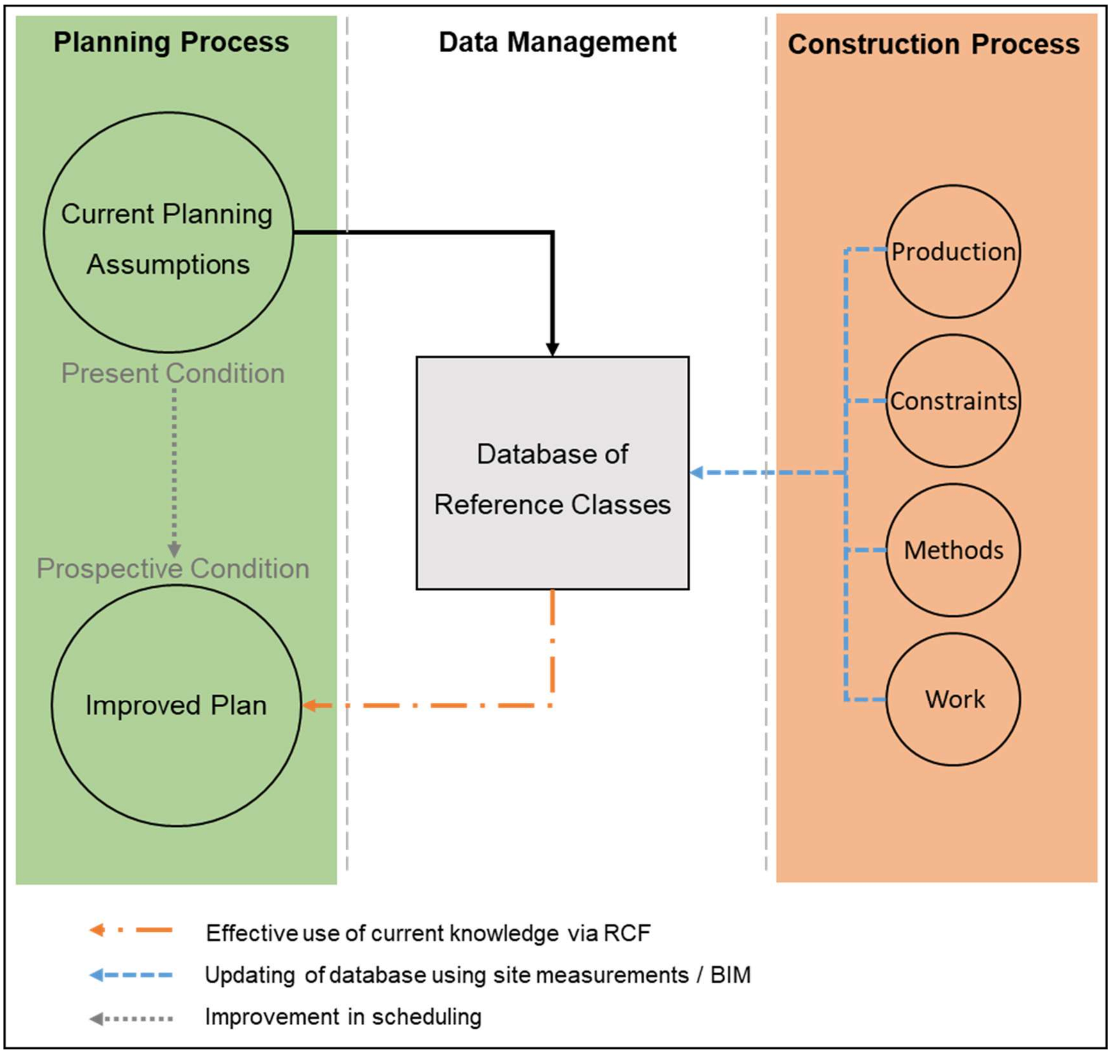


Figure 4-3. Conceptual Framework

4.5.1 Overview of Conceptual Framework

The conceptual framework provides a theoretical basis for the design and interpretation of the research by mapping-out a process where measurements of site performance may be gathered during the construction phase and stored in a database of reference classes. The data could then be interpreted and analysed using RCF to develop an improved plan, enhancing current planning assumptions with future task durations more accurately predicted using historic performance data. This research will investigate the construction process and establish suitable data to gather from the on-site activities in RC frame construction. The process of sorting and storing these data in a structured database will also need to be established, followed by the development of a process to interpret the data.

The conceptual framework consists of three sections: Planning Process, Data Management and Construction Process. Central to the framework is the Database of Reference Classes, which stores planning and scheduling data and information, informed by performance data from site. The site performance is influenced by the four factors shown under the Construction Process section on the right-hand-side of the framework, including production, constraints, methods and work. The Current Planning Assumptions, under the Planning Process section, also influence the data. The planning assumptions, heuristics and rules-of-thumb employed by planners include typical output rates for formwork and reinforcement installation and slab cycle times as indicated in Chapter 2. These details form a set of reference classes which can then be consulted to enable a prediction of future task durations, based on historic performance. This prediction process will then be performed, resulting in an enhanced construction schedule, illustrated by the Improved Plan component of the Planning Process of the framework.

4.5.2 Database of Reference Classes

The management of historic data is critical to avoiding optimism bias and the efficient implementation of RCF as outlined in Section 3.5, where knowledge management was examined. The creation of a database was researched in Section 3.5, where it was found that structure and automation are critical to efficiency. The method of analysing the data has been established in principal in Chapter 2, with formulae compiled to undertake the reference class process in Section 4.4. These factors will inform the process of constructing the knowledge base, which will be carried out in Excel and Visual Basic and validated using data collected from research participants.

It is necessary for RCF to have a number of results to form statistical inference from, and, as the database will be created for the purpose of this research it will not initially contain any data. Therefore, performance data will be collected from research participants and historic schedules to permit the reference class calculation to be performed. It is also envisaged that interoperability with BIM metadata may be facilitated through the inclusion of uniclass references, where each element or group of elements are designated a unique reference number.

4.5.3 Modelling the Planning Algorithm

To improve construction planning and overcome delays to the construction schedule, it is useful to understand the sources of construction delays (Mydin, et al., 2014). Viles *et al.* (2020) performed a broad cross-sectional literature review and found many sources of construction delay, the results of which are summarised in Table 4-1 below. A number of additional publications not assessed in the study conducted by Viles *et al.* (2020) are also presented in Table 4-1, as well as sources identified from industry experience, combined with the results of the interview opinions from Section 8.4.

Table 4-1. Schedule Delays in literature and industry

Category	Literature References							Industry Experience	
	Viles *et al.* (2020)	Hughes *et al.* (2015)	Zhong *et al.* (2015)	Cunningham (2017)	Issa (2013)	Luu *et al.* (2009)	Kim *et al.* (2008)	Influencing Factors based on Experience	Interviewee Opinion
Production									
Labour, materials, plant and equipment	✓	✓	✓		✓	✓	✓	✓	✓
Procurement				✓		✓		✓	
Constraints									
Client influence/ decision making	✓	✓		✓	✓	✓	✓	✓	
Variations / Changes	✓								
Financial	✓	✓							
External factors		✓		✓		✓		✓	✓
Weather			✓			✓	✓	✓	✓
Inadequate Risk Consideration								✓	
Methods									
Design				✓	✓	✓	✓	✓	✓
Unforeseen ground conditions							✓		✓
Work									
Physical works	✓	✓	✓	✓	✓	✓	✓	✓	✓
Project and Site Management	✓	✓	✓	✓	✓	✓		✓	✓

The schedule categories identified in Table 4-1 are the main components of delay contributing to schedule error and have been grouped under four planning parameters, as shown under the Construction Process section of the Conceptual Framework:

- Production
- Constraints
- Methods
- Work

The **production** category involves labour, plant and materials and procurement delay factors. Labour, plant and materials directly affect the execution of the works and was found by Viles *et al.* (2020) to be the most critical cause of delay, further confirmed by interview and industry experience. The Production category is concerned with the productivity of the workforce, including the outputs achieved for the erection of formwork and the installation of reinforcement. Procurement delays stem from the client's procurement process, where scope gaps and contractor and subcontractor interrelationships cause interruptions and disharmony to the smooth progression of work on site, a factor frequently experienced in industry.

The **constraints** parameter includes variations and changes to the design, or the indecision by clients in finalising choices such as concrete surface finish, for example, influencing the schedule and causes delay. Financial pressure can place a significant burden on the project as the entire supply chain can be stifled through reluctance to make payments on time. The weather, a major unknown, also places a considerable constraint on construction schedules and in particular on the construction of high-rise buildings, where significant time can be lost due to high winds affecting vertical material transportation and distribution. External factors are also categorised under the 'constraints' parameter, which includes changes to the law, increased import duty, changes to taxation arrangements, civil unrest, health pandemics and the like. Inadequate risk consideration is also categorised as a constraint, where risks are not considered sufficiently in the compilation of the schedule. For example, flooding of a low-lying site or enhanced noise restrictions due to neighbour complaints are risks which have been found in practice to be overlooked at the planning stage.

The **methods** element consists of methods of construction selected by the planner informed by the design of the structure where a strategy is developed for the construction approach, such as piling method, type of formwork, or precast concrete and hybrid construction techniques. Frequently including components designed by the contractor or subcontractor, there is often the opportunity to enhance the offering or value engineer the project through careful selection of method, although incorrect selection can cause delays through unfamiliarity of the construction process or incompatibility with other elements. For example, the installation of pre-assembled roll mats of reinforcement for floor slabs saves significant on-site reinforcement installation time, however, it can delay the overall slab construction as the column and wall transition reinforcement must be installed later which can, in practice, delay the concreting of the floor.

The **work** parameter relates to the physical work and the execution of it, including the project and site management ability. The work involved in the construction of a structure encompasses data such as kilograms of reinforcement, square metres of formwork and cubic metres of concrete. The sequencing of the works, the number and size of work crews, the crew constituents such as the ratio of carpenters to apprentices, all influence the completion of the work, with delays caused where planning has not been undertaken correctly. It is also recognised that the Project and Site Management play a crucial role in the construction phase, as it is their responsibility to manage the execution of the works, and If the management team are underperforming, the probability of project success is reduced.

It is noted that a number of the components which contribute to each parameter, such as variations or design, cannot be easily mathematically modelled and will not be included in the planning algorithm but remain heuristic, requiring the skill and judgement of the planner to develop the schedule. The components which can be modelled were previously identified in Section 2.3 above and are used to form part of the planning algorithm.

To enable the planning algorithm to function, the knowledge base will hold data which will be analysed automatically by the VB code, processing the data when a user inputs a request. Similar to data collection, the information request will be generated through a VB user form, where inputs will consist of data fields requesting details of the floor slab in question, as mapped out in the duration formulae presented in Section 2.3.1. The duration formulae will replace the manual calculations performed by the planner and will be embedded in the coding to ensure VB performs the planning calculations automatically. This procedure will then be followed by further data processing, where a reference class calculation is applied to the task productivity, resulting in a task duration proposed to the user, based on statistical analysis of historic performance.

This research proposes that the collection and analysis of production data will enhance the accuracy of construction schedule predictions. The following chapters will now address the methodology and data collection, followed by an evaluation of the questionnaire surveys. A selection of historic projects is reviewed for performance, supported by analysis of a number of industry stakeholder interviews.

The database is then compiled in Excel enabling management of the knowledge and validation of the research findings by presenting the schedule prediction tool.

4.6 Chapter Summary

Chapter 2 identified the problem in industry as inaccurate construction schedules in reinforced concrete frame construction. The measurement of performance was then evaluated, with a discussion on production rates, followed by a review of the process of schedule development from the tender schedule at bid stage to a fully developed construction schedule was also explored, followed by identification of the research question. The current literature was investigated in Chapter 3 to establish the theoretical underpinnings to the research, exploring the role of construction planning facet of project management. The science of planning was explored, establishing the planning fallacy as a potential solution to the problem of inaccurate planning. This chapter has summarised the findings of Chapters 2 and 3, extending the concept of RCF and applying it to RC frame construction.

The creation of a database, the collection of data and the formulation of a productivity baseline have all been interrogated in this chapter, with the application of RCF presented in a five-step process, including the compilation of reference class formulae suitable for inclusion in VB code. Finally, the conceptual framework was explained in terms of the research presented in chapters 2 and 3, providing a road map for the completion of the research. The next chapter will present the methodology chosen for this research, outlining the underlying philosophy, the research paradigm and the methods of data collection.

5 Methodology

5.0 Introduction

The purpose of this chapter is to describe the research methods used to undertake the study, including the methodological approach and the data collection and analysis methods. This chapter will describe the research approach, including the data collection and analysis methods, followed by a review of the ethical issues appropriate to this study.

The research question identified in Chapter 1 relates to how progress is measured, what data are required, and how knowledge can inform decision making. These have been designed to identify the root cause of construction schedule inaccuracy, and can be categorised into three factors: process, data and knowledge. As first discussed in Section 2.1 above, the aim of this research is to produce a novel tool to improve schedule accuracy in RC frame buildings. This chapter will now identify what field data is required, how it will be acquired, where it will be obtained and how it will be analysed. The instruments employed to gather data and the methods for data analysis are then confirmed. The validity, reliability, generalisability and limitations of the research will also be reviewed, with the ethical concerns related to this research then presented.

5.1 Research Paradigm

Research is guided by a set of world views or beliefs known as a paradigm, which is in essence a way of thinking about the world. The choice of paradigm is usually between positivism and the various strands of interpretivism, such as relativism, anti-positivism and phenomenology (Gray, 2020). Brown (2017) identifies a number of strengths and weaknesses to positivism and interpretivism, as summarised in Table 5-1 below:

Table 5-1. Paradigm Strengths and Weaknesses (after Brown, (2017))

Paradigm	Strengths	Weaknesses
Positivist	• Relationship between variables can be modelled • Generalisable models • Analysis can be rapid and economical	• Inflexibility of methods • Involvement of researcher in the research
Interpretivist	• Data collection is naturalistic • Deep meanings may be developed	• Data collection often protracted • Data analysis can be difficult • Credibility of research often questioned

Having reviewed competing paradigms and discounted them as the strength of the researcher conducting this study lies in numbers, this research is approached from the positivistic end of the continuum. Although it may be possible to perform this research from a more interpretivist position, it is considered that the meanings behind the data would be more difficult for the researcher to uncover than applying a numerical method to the data collection and analysis. With positivism, the belief exists that the truth is available to be discovered by performing experiments, tests and statistical analysis on the data collected. It is also held that, within the context of an organisation, the relationships between variables may be modelled and that generalisable models may be developed for task duration prediction, based on statistical analysis. However, there are a number of drawbacks associated with positivism, such as the inflexibility of the methods and the inextricable involvement of the researcher in their research, where the researcher is unable to remain purely neutral but will be influenced by the researchers' own preconceptions, values and beliefs of the planning process (Brown, 2017). This research is approached from a less extreme post-positivist position similar to Parry's (2015) analysis of delays in the UK construction industry, acknowledging that reality is represented as the best approximation of the truth, where there is a belief that the research findings will predict future schedule outcomes with a degree of confidence rather than absolute certainty.

5.2 Research Approach Selected

This research is undertaken using a mixed methods approach, mainly from the quantitative perspective, principally because the construction industry operates in a quantitative manner, driven by logical and numerate engineers and quantity surveyors, as is the researcher conducting the research.

There are two general categories of research approach, known as quantitative and qualitative (Trafford & Lesham, 2008). Qualitative research, according to Creswell and Creswell (2017), is an approach used to explore and develop an understanding of the meaning individuals attach to a problem, where a 'rich, thick description' is used to convey the findings in detail. Frequently involving interviews and observations, qualitative research does not usually involve formal measurements as is the case in this research, but is conducted through 'intense contact' (Gray, 2020). The emphasis of qualitative research data is on words rather than quantities and cannot be evaluated or counted precisely (Walliman, 2018). Quantitative research is an approach where developing and testing of hypotheses, generating theories and models to explain behaviour, and the generalisation of results are the main concerns of the researcher (Hoy & Adams, 2016). The data produced from quantitative research may be measured with a degree of accuracy as they are usually expressed numerically, containing some scale of magnitude (Walliman, 2018) and can be analysed using descriptive and inferential statistics (Gray, 2014; Gray, 2020), as discussed below in Section 5.3.4.

5.2.1 Mixed Methods Research Design

As the conceptual framework of this research proposes that enhanced forecasting may be achieved without full control exercised over the variables, it is therefore deemed to be quasi-experimental quantitative research design. In this design method, the results of the planned and actual data will be used to expose the error in output prediction. This error will then be used in conjunction with RCF to inform the planner of the error value to be applied to their estimated durations. With quasi-experimental research, the sample taken from the target population is not randomly selected by the researcher. There are a number of advantages and disadvantages to quasi-experimental design, as pointed out by Russ-Eft and Hoover (2005) and Reichardt (2009):

Table 5-2. Advantages and Disadvantages of Quasi-Experimental Research

Quasi-Experimental Research	
Advantages	**Disadvantages**
• It is practical and usually generalisable so may be applied company-wide to all projects • Threats to internal validity can be controlled through control of the productivity data gathering process	• Inability to manipulate the independent variables, such as workforce capabilities • Inability to randomly assign the sample as there will be choices made in the selection of data to analyse • Risk of erroneous interpretation of validity of results where past schedule performance does not necessarily indicate future schedule performance.

Descriptive research measures a sample and describes the current condition using the existing data, often concerned with describing the 'average' member of a sample (Marcyzk, et al., 2005). Johnson and Christensen (2019) outline three forms of non-experimental research, which they define as descriptive, predictive and explanatory research. Experimental research, on the other hand, tests a theory and measures the cause and effect of independent variables on a dependent variable (Lowthorn, 2007).

Experimental research is based on experiment or test, defined as a test under controlled conditions to demonstrate a known truth or examine the validity of hypotheses (Muijs, 2010).

5.2.2 Justification of the Design

The selection of research design is guided by the research philosophy, the methodical choice, the research strategies, the time horizon and techniques and procedures, as shown in the Research Onion in Figure 5-1 below. The selected research design for this study has been highlighted in red, showing that it is undertaken from a positivistic philosophical perspective using mixed methods and a survey strategy, with a cross-sectional time horizon.

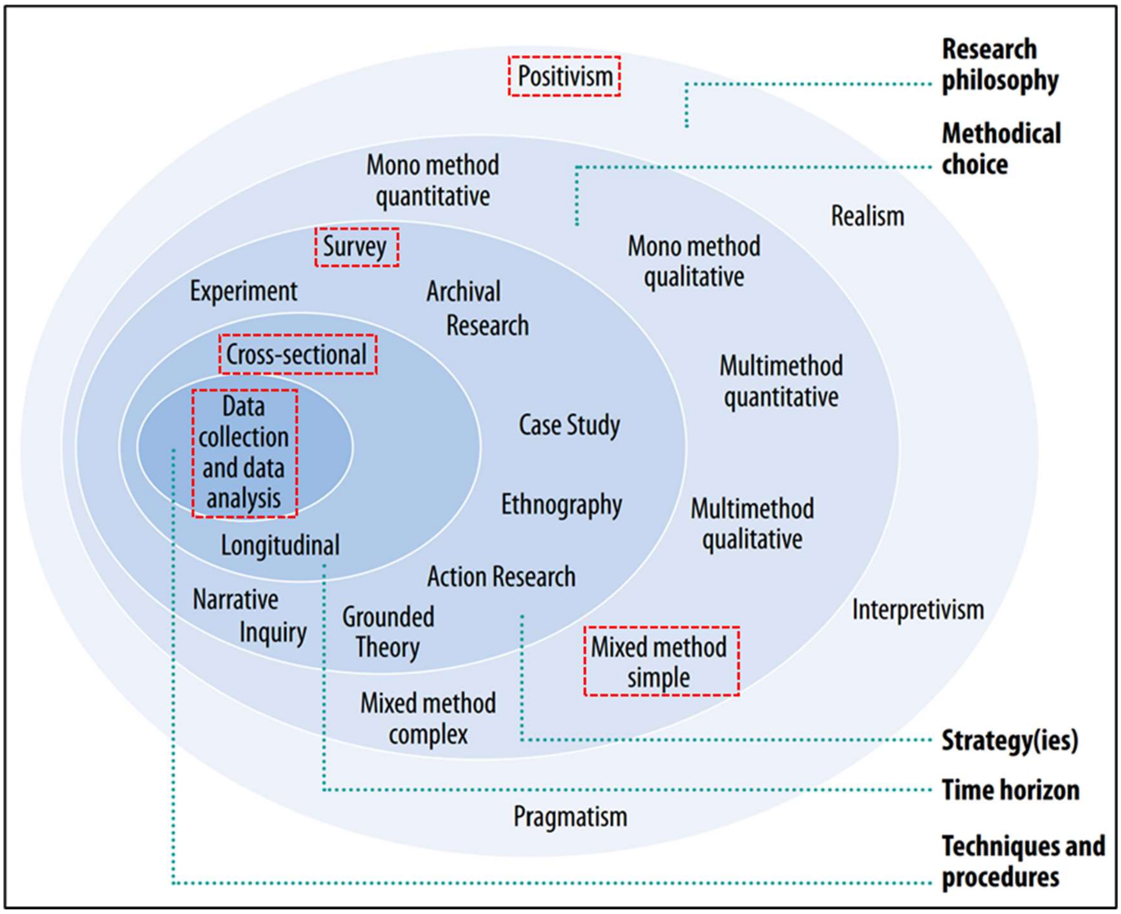


Figure 5-1. The Research Onion (Saunders & Tosey, 2012)

5.2.3 Research Design Identification

Trafford and Lesham (2008) suggest a suitable template to identify a research design is provided by Kipling's 'Six honest serving men' that is, the words 'what, why, when, how, where and who', as responses to these questions will assist researchers in making decisions to shape their research design. The 'what' of this study is provided by the aim outlined in Chapter 2 above, which is to produce a novel tool to improve construction schedule accuracy in reinforced concrete frame buildings, achieved through the creation of a database of knowledge of previous construction schedule performance. This may then be analysed to provide more accurate predictions for future planning and scheduling decisions.

The reason why this research has been undertaken is to solve the problem of inaccurate scheduling in current practice, identified through a state-of-the-art review of planning and scheduling (Chapter 2) and analysis of the existing literature (Chapter 3). The data collection for this research was undertaken in 2019 and included reviews of historic RC frame construction schedules, questionnaire surveys and interviews, with the analysis of the data performed in 2019 and 2020. The review of construction schedules was a desktop study, whilst the questionnaire surveys were hosted online and distributed through email and a social media channel. The seven interviewees were selected from internal and external candidates who have specific knowledge of productivity and durations related to RC frame construction in the London, UK market. The interviewees included planners, directors, contract managers and project managers, with the interviews conducted either face to face or, in two cases, via telephone.

Table 5-3. Kipling's Six Honest Serving Men, after Trafford and Lesham (2008)

Question	Answer
What	To produce a novel tool to enhance schedule accuracy.
Why	To solve the problem of inaccurate construction schedules in RC frame construction.
When	The data was collected in 2019 and analysed in 2019 and 2020.
How	Desktop studies, questionnaire surveys and interviews were used to collect data.
Where	The research was undertaken in London, UK
Who	Planners, project managers, contract managers and directors

5.2.4 Research Process

The research process commences with the gathering primary data from questionnaires, followed by interviews and historic project documents and the use of this data to develop a database of planning knowledge, which will then be used by a planning tool to predict task durations, based on past performance, as shown in Figure 5-2 below.

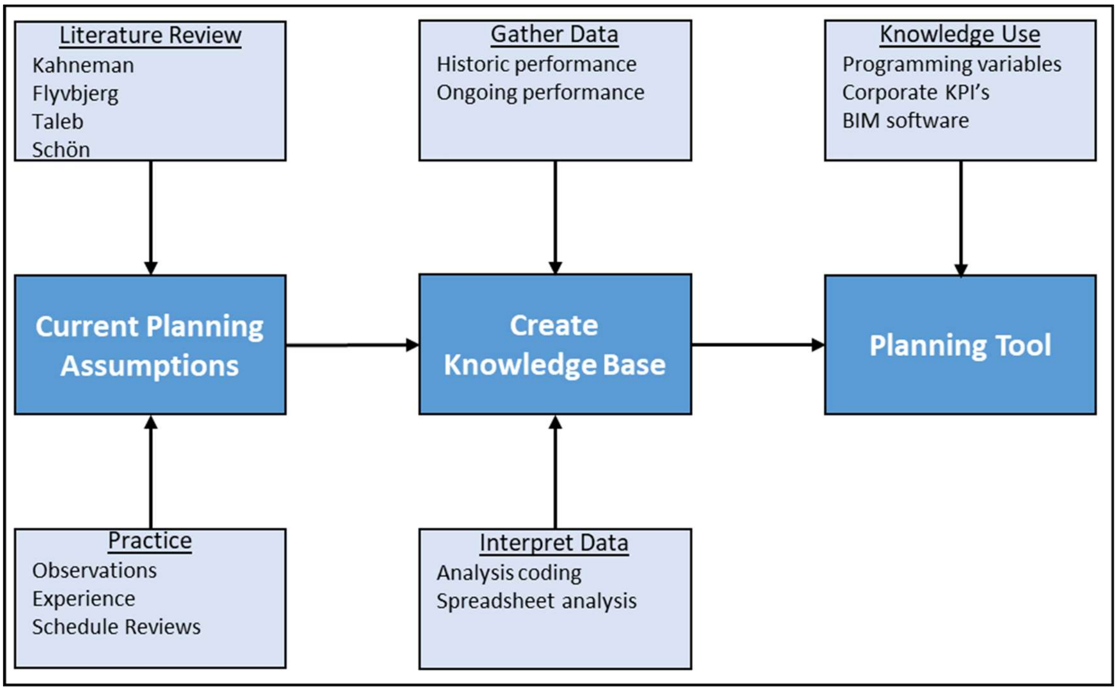


Figure 5-2 Research Outline Model

5.3 Quantitative Data Collection

This section relates to the collection of data from Reference Classes and includes data collected from questionnaires.

5.3.1 Questionnaire Data Collection

Grey (2020) notes that there are two types of data, primary and secondary, where primary data is data that has been collected for the research in hand, whilst secondary data has been collected for a previous purpose. With regard to primary data, the most common sources are surveys, interviews and observations (Gray, 2020), although Walliman (2018) categorised primary data collected by researchers into four forms, as follows:

1. Measurement – numerical data, such as metres, kilograms or days.
2. Observation – records of situations or experiences, encountered with the senses
3. Interrogation – data collected through asking people probing questions
4. Participation – involvement by the researcher to experience the phenomena

In this research, the questionnaire survey will mostly be concerned with the collection of measurement data, therefore the most prevalent forms of primary data collection will be measurement and interrogation.

Primary data retain the advantage that they are collected expressly for a specific research question, therefore directly relate to the phenomena under consideration, are not out of date, and the researcher can retain confidence in the authenticity of the data (Adams, et al., 2007). Walliman (2018) emphasised the robustness and reliability of primary data in comparison to secondary data, as the facts will not be distorted by the interpretation of another researcher. There are a number of disadvantages to using primary data, however, with response rate to questionnaire surveys being a primary concern (Gray, 2020). Walliman (2018) highlights that primary data collection is frequently expensive and time consuming to undertake, whilst Neelankavil (2007) points out that primary data sources are sometimes inaccessible or unavailable to the researcher, such as data relating to events which have occurred in the past.

Secondary data can take many forms, as it is a review of material produced by another researcher. For this reason, Gray (2020) states it would be impractical to provide an exhaustive list of secondary data sources, with the more popular including archives, personal and organisational documents, professional and technical reports and academic sources. There are several benefits to using secondary data, such as the lower cost and effort required to obtain the data, which is collected in a shorter time frame, enabling analysis to be commenced earlier (Gray, 2020). Furthermore, the data sets available are expansive, suitable for the analysis of longitudinal data (Adams, et al., 2007) and allow the researcher a degree of objectivity as the original data may be re-analysed (Gray, 2020).

There are a number of disadvantages associated with the use of secondary data, according to Gray (2020), including the possibility that the data is partial, out-dated, imprecise, biased or of poor quality. Walliman (2018) concurs, holding that the most important consideration is an assessment of the data and information provided. However, it is recommended that secondary data is compared with data from different sources, which can include primary and secondary data, to permit the identification of any bias or inaccuracies and allow contrasting interpretations to be exposed (Walliman, 2018).

The phenomenon of inaccurate scheduling has been noted in Chapter 1 above and to investigate this phenomenon further, a questionnaire was developed with a view to uncovering the underlying reasons for inaccurate scheduling. Following the questionnaire survey, further primary research was undertaken in the form of interviews, whilst the secondary data collected comprises of an unobtrusive study where analyses of historic documents is undertaken, including project documents, reports and spreadsheets.

5.3.2 Questionnaire Sampling

It is challenging to determine a randomised sample of the population because it is difficult to establish the population size, as there is an undefined number of stakeholders in the construction industry with interest in knowledge management, planning and scheduling in the RC frame construction sector. In common with the findings of Ogunbiyi *et al.* (2014) in their study of lean construction in the UK, convenience sampling was deemed appropriate for this research as there is no comprehensive, nor any standard, database of construction organisations in the UK involved in RC frame construction.

With non-randomised convenient sampling, a sample of the population is chosen based on convenience for the researcher where subjects are readily available, easy to contact, easy to access and willing to partake (Ogunbiyi, et al., 2014). A sample size of 70 was chosen as an appropriate quantity of questionnaire survey respondents, based on two previous studies. In the first, Carillo *et al.* (2004) undertook research in knowledge management in the UK construction industry and based their findings on a questionnaire survey of 53 responses, whilst in a later study, Ogunbiyi *et al.* (2014) performed analysis on 55 questionnaire survey responses in their study of lean construction.

5.3.3 Design of Questionnaire

The questionnaire survey was designed to elicit data on how progress is measured, the data required to measure progress, and the influence of RC frame construction on the overall client project construction schedule. There was a total of 25 questions posed on the questionnaire, with the quantity of questions chosen to permit completion of the questionnaire in a time of less than 10 minutes in an effort to avoid partial completions, with sufficient questions posed to gather adequate data. The questionnaire was divided into sections, with each section contained on its' own page within the online survey, approximately grouping similar areas of enquiry together. The first section contained five questions related to the demographic breakdown of respondents, relating to age group, education level, job title, professional memberships and length of experience in the construction industry. This was to confirm that the respondents possessed the ability to understand the questions posed, and possessed relevant industry experience. Prior to conducting the questionnaire survey, it was recognised that some of the respondents, such as clients or consulting engineers may have an interest in or be affected by progress, but do undertake progress assessments and therefore do not have knowledge, for example, on the intricacies of measuring progress in RC frame construction. It was a strategic consideration during the design of the questionnaire that it is necessary to include this set of respondents, as they will possess valuable data with regard to their expectations for production rates. Therefore, skip logic was introduced to the questionnaire, with the respondents divided into two streams, Group A and Group B, based on the reply to Question 6: 'Do you measure progress in RC Frame projects?'. This gave the opportunity to ask those who directly assess progress and those who have intertest and knowledge of construction progress to partake in the study. Without this streaming, the data would be combined and the results may not be clear. For example, it is possible that those who assess progress have a clearer idea of the specific outputs for reinforced concrete frame tasks, whilst others may not. The response and consequential streaming gave two complimentary sets of responses to the remainder of the questionnaire, as shown in Table 5-4 below.

Table 5-4. Streaming of Questionnaire Responses

Response Group	Description
Group A	Those who assess progress
Group B	Those who are interested in measured progress

This streaming or grouping allowed specific questions tailored to the respondents, such as frequency of monitoring and the methods they use to monitor. Following the initial demographic questions which were common to all, those that did measure progress were guided towards 10 specific questions, with the remaining respondents streamed to answer 7 similar questions. Figure 5-3 below illustrates the design of the questionnaire, with the questions given in full in Appendix A.

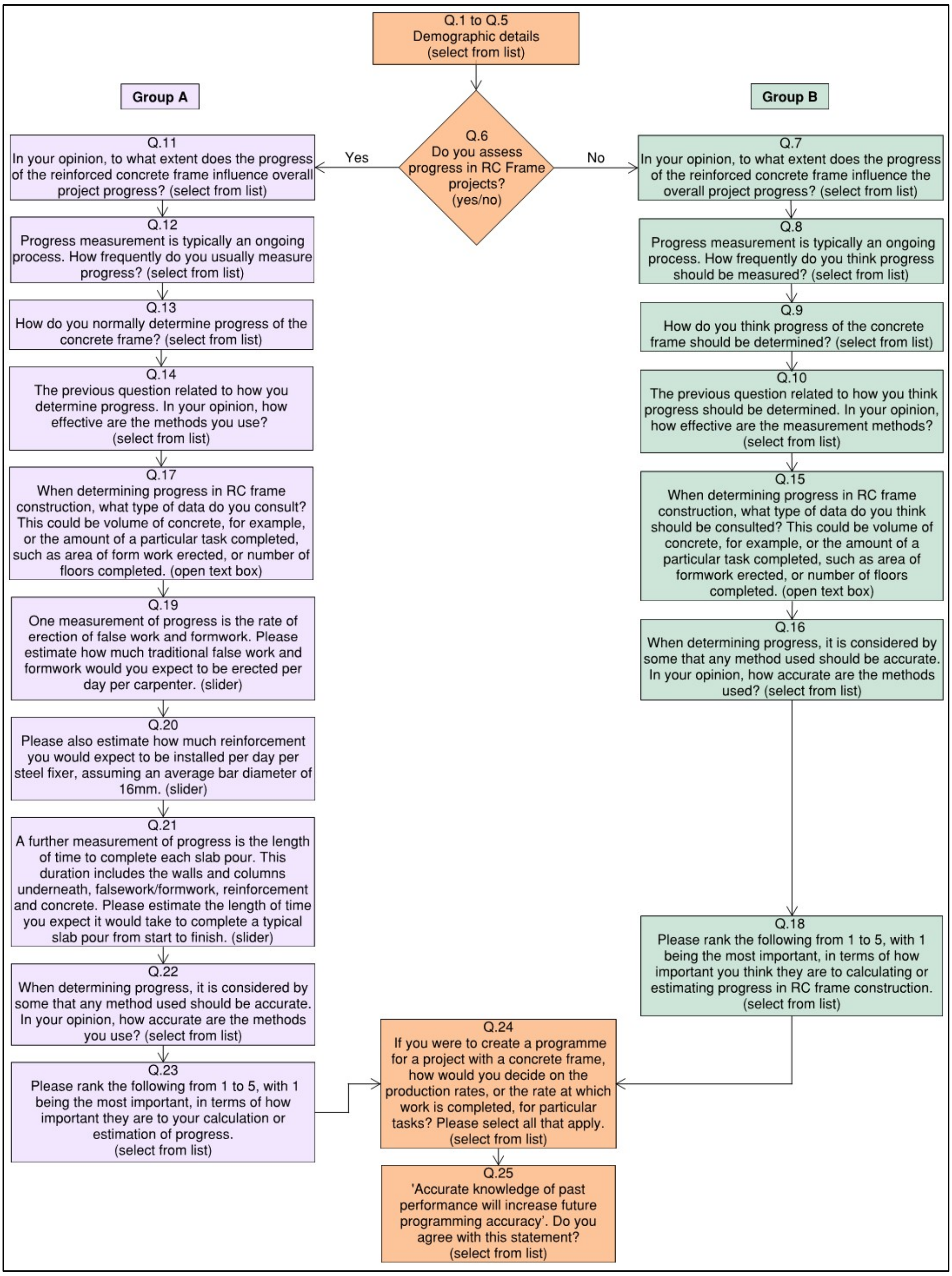


Figure 5-3 Questionnaire Design

The second section of the questionnaire survey related to the measurement of progress, in an effort to ascertain how progress is measured in RC frame construction. To explore this area, a number of questions were included relating to the methods used to assess progress, the perceived effectiveness of the assessment method, the frequency at which progress is measured and the effectiveness of the processes used. The third section of the questionnaire was designed to investigate what data are required by respondents to measure progress, including the expected output from carpenters, steel fixers and the predicted slab cycle time. The final section of the questionnaire involved questions to investigate the influence of RC frames on the overall client project construction schedule, included to seek justification for the research into RC frame projects.

5.3.4 Questionnaire Data Analysis

The data analysis will be undertaken manually in Excel using descriptive and inferential statistics, with details of the formwork and reinforcement outputs and slab cycle times collated and analysed. Descriptive statistics will be used to summarise the findings of the data collection process, presenting the questionnaire survey results in diagrammatic and tabular form where the data can be inspected, permitting response frequencies and trends to be displayed. Inferential statistics will also be used, where significance testing will be performed to establish dependency between variables, such as the probability of the method of progress assessment and the accuracy of the measurement (Questions 13 and 22 respectively, refer to Figure 5-3) being dependant variables.

Similar data will be gathered from the interviews and compared with the results of the questionnaire survey to corroborate the data. Analyses of the six construction schedules, project documentation and associated files will also be undertaken to establish a baseline of productivity data to create a planning knowledge database, with triangulation between the data providing reliability and validity.

When the baseline has been established, and the data entered from the historic construction schedules, code will be compiled in visual basic which incorporates a reference class calculation. This code will allow the user to enter project data which will then mine the database and propose a duration for the task in question. The duration will be a based on the geometric properties of the RC frame as typically executed by planners and take the form of a RCF using the database of reference projects.

5.4 Interviews

Similar to the questionnaire survey, the following section also relates to the collection of data from Reference Classes, as conducting interviews allowed the triangulation of quantitative data gathered from different sources, enhancing the reliability of the results and, in this study, clarifying the findings of the questionnaire survey. The interviews were initially considered only as a potential method of data collection; however, the interview method was deemed necessary to verify the questionnaire survey results through triangulation and gather qualitative data in the form of views and opinions of participants. Furthermore, it was considered possible that those in Director and Contracts Manager roles may assess progress with less accuracy and in a different way to Planners and Project Managers, something which could be verified through interview but would be difficult to ascertain through a questionnaire. Finally, the use of interviews as a data collection instrument allowed the researcher to confirm first-hand the views of relevant staff within the organisation with regard to how they measure progress, the data they measure, and what factors have the greatest influence on construction schedules.

5.4.1 Interview Data Collection

Interviewing is a technique widely used in research to gain details of people's experiences, preferences and perceptions (Costley, et al., 2010), and, although particularly useful where qualitative forms of data are required (Walliman, 2018), interviewing is also a suitable tool for the collection of quantitative data (Gray, 2020), permitting verification and triangulation of the quantitative data gathered from the questionnaire. There are three categories of interviews, according to Gray (2020), as follows:

- Structured interviews are used to collect quantitative data, with the same questions posed to each interviewee in the same order
- Semi-structured interviews are non-standard interviews where the broad question topics are discussed, where the interviewer may pose additional questions during the interview, facilitating probing of candidates' views. Questions are typically open-ended and are used to gather both qualitative and quantitative data.
- Unstructured interviews do not have any pre-set questions, where the interviewer poses open-ended questions to elicit qualitative data from the interviewee, taking the form of a 'guided conversation'

As this research is designed to uncover mainly quantitative data, semi-structured interviews were chosen. The strengths associated with semi-structured interviews are that, in terms of time and cost, they are economical to carry out and facilitate straightforward analysis as the data set is derived from a fixed set of questions. The semi-structured interview permits insight into participant perspectives, thoughts and experiences, whilst also providing the best opportunity to gather factual data, affording quick data collection with interviewee anonymity assured (Gray, 2020). The main limitation of structured interviews is the lack of flexibility as impromptu questions cannot always be posed by the interviewer, however the use of semi-structured interview technique allows the interviewer to pose probing questions as the interview unfolds, with the possibility of exploring unforeseen areas with the interviewee. To facilitate this, a suitable set of questions was developed, deemed to cover sufficient ground to obtain the quantitative data required. A further drawback of semi-structured interviews is that the interviewee can interpret the question in a particular way, not as the researcher intended, although with the interviewer present clarification can be given immediately.

5.4.2 Interview Sampling

The selection of interviewees was designed to achieve a balance of candidates, with five internal and two external to the researcher's organization. The external candidates viewed as essential to achieve balance, rather than the findings being skewed by the operational processes of one organisation. The interview candidates comprised of two Planners, two Project Managers, a Contracts Manager and two Directors, as outlined in Table 5-5 below.

There are four planners, 14 project managers, three contracts managers and six directors within the organisation. Drawing at least one candidate from each of these professional groups internally seemed appropriate, with a second director consulted for their over-arching knowledge of operations. This gave a sample of five from 27, or 19% of the population. The two external interviewees were chosen for convenience, as they are known to the researcher and deemed to have sufficient subject knowledge.

Table 5-5 Profile of Interview Candidates

	Planner	Project Manager	Contracts Manager	Director
Internal	✓	✓	✓	✓✓
External	✓	✓	×	×

5.4.3 Design of Interview Questions

Reliable, factual data were a primary concern in this research and therefore the questionnaire survey in Figure 5-3 above used as a template for the interview questions. A set of 15 questions were posed at each interview, identical to the questions posed to Group A in the questionnaire survey. Each question was read out to the interviewees by the researcher and all interviews were recorded and transcribed by the researcher. Once transcribed, a copy was sent to the interviewees, with all confirming that their answers were recorded correctly.

5.4.4 Interview Data Analysis

The interviews were designed to explore in more detail the initial findings of the questionnaire survey and investigate further the methods of progress measurement and the influence of RC frames on the project schedule. The data was also analysed statistically with regard to outputs and SCT, permitting comparisons to be made with the questionnaire data.

5.5 Unobtrusive Research

Unobtrusive Research is similar to questionnaire and interview methods described previously and involves the collection of secondary quantitative data.

5.5.1 Secondary Data Collection

The principal emphasis of the secondary data collection in this body of research is to identify the predicted productivity for RC frame projects and compare it with the productivity actually achieved on site. This is performed through a method of enquiry described by Gray (2020) as unobtrusive research involving the use of non-reactive sources of data, encompassing organisational, personal and business records. The use of unobtrusive research is beneficial to this study, as the archive of data exists and was accessible, taking the form of both paper and electronic documents consisting of construction schedules which contain planned and actual progress records, periodic progress reports, meeting minutes and productivity spreadsheets which contain organisational productivity baseline values.

Gray (2020) notes that unobtrusive measures deal with ‘dead’ data, which is data from non-reactive sources and therefore is not subject to the same biases that interactive research encounters. Gray (2020) notes that a number of biases are overcome when using unobtrusive methodology, including interviewer bias, reactivity between interviewer and interviewee, misinterpretation of questionnaire survey questions and research tools of questionable validity and reliability. As with other methods, there are drawbacks with unobtrusive research such as the representativeness of the sample taken, or the possibility of inaccurate or incomplete data (Gray, 2020). A further concern is the suitability and validity of data collected by others, where the original researcher may have influenced the data with their inherent bias or where the subjects of the research adjust their behaviour as they are aware they are being studied, a phenomenon known as the Hawthorne effect (Adams, et al., 2007). Gray (2014) recommends that an unobtrusive approach is augmented by other methods, with Powers and Knapp (2011) advising that a combination of obtrusive and unobtrusive approaches are used.

5.5.2 Secondary Sampling

A company-wide internal database of projects was consulted and a random selection of 30 RC frame projects were chosen, with a further six projects sourced externally, giving a long list of 36 construction schedules which were then examined for suitability. The review consisted of assessing suitability according to five criteria as follows:

1. The project must include a reinforced concrete frame, to ensure relevance to the research area.
2. Construction schedules must be available in the native planning software file to ensure progress and resource records can be fully interrogated and verified (Keane & Caletka, 2015)
3. Each project is to have a duration greater than an arbitrary duration of 6 months, as short duration projects can exhibit skewed labour resources and adversely affect productivity (Hofstadler, 2017).
4. The construction schedule is to contain a sufficiently detailed work breakdown schedule. A high-level construction schedule of compound tasks with long durations would contain insufficient detail rendering analysis fruitless (Siami-Irdemoosa, et al., 2015).
5. The project has commenced within 5 years of 2020 to permit a fair comparison and maintain a level of currency. A time boundary is necessary as technology and construction methods change over time, affecting productivity rates (Loosemore, 2014).

Based on the above criteria, each construction schedule from the group of 36 was examined for suitability, with most being discounted due to incomplete records of progress or exhibiting insufficient detail to permit a rigorous analysis of the data. The long list of 36 schedules was then reduced to a short list of six which were deemed suitable, including two construction schedules provided by interviewees.

Project records, in the form of progress reports, are also required as part of the enquiry because the schedules contain insufficient information to calculate productivity, in particular the number of personnel engaged in specific site activities. In addition, the internal Planning Spreadsheet will be consulted to determine the tender planning productivity rates applied at tender stage. The use of these three elements – historic construction schedules, progress reports and the Planning Spreadsheet – will permit triangulation with the data gathered from the questionnaire survey and the interviews.

5.5.3 Design of Enquiry

The premise of the unobtrusive research was to gather historic performance data from selected projects with regard to formwork erection, reinforcement installation and slab cycle times.

5.5.4 Secondary Data Analysis

The data was gathered in order to develop a database of planning knowledge, with a view to predicting future planning decisions. The overall planned durations for formwork, reinforcement and SCT were extracted from the schedules, as were the achieved durations, and, together with the associated labour levels, allow determination of the planned and actual output levels.

5.6 Capturing Tacit and Explicit Knowledge

In Chapter 3 reference was made to Nonaka's (1991) SECI model of organisational learning, where tacit knowledge is converted into explicit knowledge. Development of the tool will address the three elements of the SECI model as identified by Sarirete and Chilkh (2010) as follows:

1. Four modes of knowledge conversion between explicit and tacit are identified in the SECI model, although the tool will not be designed to facilitate all four modes (for example, *socialisation* will not be enabled). The tool will *externalise* tacit knowledge into explicit through user inputs and user-defined categories of data collection, whilst *combination* will occur through the storage and processing of information in the knowledge database, with i*nternalisation* of the explicit knowledge will be promoted through offering the user durations with enhanced accuracy.

2. The *Ba*, or shared context, will be the tool itself, which collects data and converts it into information and knowledge.
3. The *knowledge assets* will be the virtual knowledge database of reference classes, such as production rates and slab cycle times.

The tool is not intended to be a replacement for tacit knowledge; the user will require their tacit knowledge to create a schedule based on the durations suggested by the tool, with elements of the project remaining within the judgement of the planner, such as assessments on the impact of weather, traffic congestion or construction sequencing.

5.7 Testing

The processes required developed to collect interpret and store site performance data and to subsequently perform RCF will require testing to ensure they are functioning correctly; it is anticipated that the testing will take the form of three stages:

1. Initial Testing

   The initial testing will examine the collection, storage and analysis of the performance data, ensuring the processes are executed correctly.

2. Task Duration Prediction

   The second strand of testing will involve the results of the data analysis and the proposed task durations and consider if increased task duration accuracy is achieved. Historic performance data may be used for this purpose, permitting a comparison between predicted task durations and actual outcomes.
3. Industry Testing

   The final testing will be carried out in industry, where planners will be requested to enter project data and develop task duration predictions for tender schedules. The actual durations achieved on site will then be compared with the forecast duration, allowing the prediction error identified.

5.8 Research Ethics

It is incumbent on the researcher to carry out the study with honesty and integrity (Adams, et al., 2007). Research ethics refers to the moral principles guiding research, where the research is conducted in a responsible and morally defensible manner (Gray, 2020). Kaufmann (2020) observed that ethical conflicts may arise when conducting research within one’s own professional environment, whilst Ryen (2016) indicates that the main concerns of ethics as follows:

- Informed consent
- Confidentiality
- GDPR
- Trust
- Integrity
- Credibility

5.8.1 Informed Consent

Informed consent means that research subjects have the right to know that they are being researched, the right to be informed about the nature of the research and the right to withdraw from the research at any time (Ryen, 2016). Acknowledging that the extent of the information given to participants should be proportional to the degree of risk involved, Gray (2020) provides a list of information that would often be provided to research subjects to achieve informed, voluntary consent:

- The aims of the research
- Who will be undertaking it;
- Who is being asked to participate;
- What type of information is sought;
- How much time is required from the participant;
- That participation is voluntary;
- Who will have access to the data after it is collected;
- The measures taken to maintain anonymity of participants.

5.8.2 Confidentiality

Confidentiality and the right to privacy is fundamental to a democratic society, according to Gray (2020) and the participants must be given the option to refuse to answer any question that makes them uncomfortable or withdraw from the research entirely. There is an obligation to protect the identity of participants and a legal requirement on the researcher to protect data and restrict access to personal data, which includes facts and opinions as provided for in the Data Protection Act, 1998 (Gray, 2020).

5.8.3 GDPR

General Data Protection Regulation is a law regarding data protection and privacy, where it remains incumbent on the collector of personal data to provide anonymity so that subjects cannot be identified from the data (Gray, 2020). Participants in interviews have been anonymised and it is not possible to identify the questionnaire participants as this data was not collected.

5.8.4 Trust

Trust (Ryen, 2016) and the avoidance of deception (Gray, 2020) refer to the relationship between the researcher and the subject. Honesty is essential to develop trust and open communication, enhancing the level of credibility of the research. It is also the responsibility of the researcher to avoid the creation of a negative reputation for researchers which may reduce future participation cooperation (Gray, 2020) and 'spoil' the field for others (Ryen, 2016).

5.8.5 Credibility

The credibility of the research is related to the extent to which interpretations can be confirmed as factual, accurate and dependable. It is the closeness of fit between the research data and the researcher's representation of it. Credibility will be assured in this research through rigorous and honest treatment of the data analysis and the accurate reporting of results. References have been taken from trustworthy sources such as academic journals and reputable publishers, with all quoted sources identified in the bibliography.

5.8.6 Integrity

Research integrity refers to the manner in which the research is undertaken which allows others to have faith and trust in the research findings. Honest, accountable, fair and responsible research underpin research integrity, which have been provided for in this research through the careful and methodological exclusion of plagiarism, mistruths and deception.

5.8.7 Potential Ethical Conflicts

A number of ethical conflicts have been identified with regard to this research, as outlined in Table 5-6 below, including the measures taken to mitigate the ethical risk.

All of these potential ethical conflicts in Table 5-6 below were taken into account in line with Anglia Ruskin University's ethics policy and, following the researcher's completion of the University's compulsory ethics training, a Research Ethics Application Form was submitted to the School Research Ethics Panel. Ethics approval for this research was received on 19/10/2018, approval number EB18-010; please see

Table 5-6. Ethical conflicts and mitigation measures

Ethical Conflict	Mitigation Measures
Informed consent	Participation consent form to be signed by participants
Confidentiality	Electronic data will be kept on a password-protected computer. Documents kept in a locked filing cabinet for a period of three years and then destroyed.
Accuracy of interview transcript	A transcript of the data collected at interview will be sent to each participant for verification.
Access to organisational data	Written permission will be obtained from the data owner
Judgement of productivity	The accuracy of construction schedules will be explored to identify trends. No individuals, companies or projects will be identified.
Health and Safety	All face-to-face interviews will be held either in a corporate head office or a public place ensuring safety for both interviewer and interviewee.

5.9 Reliability

Reliability or trustworthiness is concerned with consistency of measurement, a measure of the stability of the findings, with Gray (2020) stating that care with the selection of a sample population must be exercised, something which Cook (2015) described as 'purposeful selection'. Reliability may be established through a demonstration that the operation of the research, including data collection procedures, may be repeated with similar results produced (Collins, 2010). The reliability of a body of research, according to Connelly (2016), refers to the degree of confidence in data, interpretation and methods used and is related to the credibility, dependability, transferability and confirmability utilised to guarantee the quality of the study.

Trustworthiness of the data was critical at all stages of this research, where it was planned and executed with a view to ensure reliability. This was achieved by using a triangulation method of data collection (Hughes, 2020), where anonymous questionnaire surveys, interviews and document analyses was used. With regard to the questionnaire surveys specifically, the credibility was initially established by only including respondents with construction industry experience, where all of the participants work in the construction industry (Hughes, 2020). Anonymity provided confidence that the respondents would not be identified and could respond honestly and openly to the questions posed. Gray (2020) agrees with this interpretation of reliability, noting that reliability may be achieved through the use of multiple data collection instruments, which is the case in this research where, for example, questionnaire surveys and interviews were used to gather primary data, whilst scholarly journals and multiple construction schedules were analysed to collect secondary data.

5.10 Validity

The validity and reliability of the research methods or tools used to collect research data must be established to enable defendable inferences or deduction of conclusions from the data gathered (Brown, 2017). The validity of research is dependent on the accuracy of data and, as Gray (2020, p. 151) argues, validity is defined as having several components, but essentially centres around one question: does ‘a measure of a concept really measure that concept – does it measure what it *claims* to measure?’ (emphasis in original text). Seppänen concurs, contending that validity may be improved through the use of multiple sources of data and information (Seppänen, 2009). In the case of this research, multiple primary and secondary data sources have been utilised in to increase validity: questionnaire surveys, interviews, construction schedules, project reports and internal documents and files. External validity is improved through the inclusion of multiple RC frame projects of varying sizes, durations and values, including two external projects which demonstrated similar results as shown in Chapter 7 below.

5.11 Methodological Limitations

5.11.1 Questionnaires

The responses to the questionnaire benefited greatly from promotion on social media, however, it is considered that additional responses could have been achieved if a diverse range of professional bodies were also contacted, for example the ICE or RICS, as the social media promotion by the APM coincided with a surge in questionnaire completions.

The duration that the questionnaire remained available was five months, and whilst this did produce 70 usable responses, it is believed that extending the availability of the questionnaire for an additional period would yield further responses. However, in terms of the timeframe for the study, this was impractical and in September 2019, having reached 70 responses, it was decided not to extend the questionnaire availability.

5.11.2 Unobtrusive Research

One limitation of this study is that the majority of construction schedule analyses involved the data of one company, augmented by two external data sets, potentially impacting on claims of validity, reliability and consequently, generalisation.

As project performance is a commercially sensitive topic, access to data was restricted and therefore competitors were reluctant to release projects to be studied, with the exception of the two organisations that released information on only one project each. Due to the mainly statistical, quantitative nature of the study, the accuracy of duration predictions is proportional to the quantity of production data gathered; therefore, it stands to reason that increasing the number of projects analysed would enhance the accuracy of the results.

5.11.3 Interviews

The main limitation in the execution of the interviews was that the respondents were recalling outputs from memory, which meant that there is the possibility of memory bias existing in the responses received. Furthermore, the researcher's lack of experience in conducting interviews meant that the initial interviews were not performed as smoothly as those conducted later. Also, as some interviews took place over the telephone, it was not possible to take visual clues from the interviewees, potentially reducing the richness of the data gained.

In terms of generalisation, it could be argued that specific results may be generalised for similar circumstances and situations, that is, flat RC slabs in the London region. There is a large number of standard geometrical arrangements available to designers of concrete slabs, with each one affecting formwork erection and removal durations and concrete curing time differently. Therefore, collecting data on several different geometric shapes and shape combinations would enrich the database, facilitating data collection in the future. In terms of geographical limitations, the study was undertaken in London in the United Kingdom; it would therefore be preferable to undertake the study in other areas, but as this is the working area of the company originally facilitating the research, the study was limited to this region. A further limitation is related to the global COVID-19 pandemic which stifled construction in 2020 and had a limiting effect on access to data, people and projects. However, it is considered that the data collected is sufficient to develop theories and draw conclusions from.

5.12 Summary

This chapter described the research method for undertaking the research, outlining a mixed methods approach to the collection of data. In terms of the philosophical position of the researcher, this study is performed from an objectivist perspective recognising that, ontologically, the reality and truth exist and needs to be found; in other words, an objectivist theoretical perspective will be used. The purpose of this research is to uncover the truth, that is, answers to the research question with an emphasis on rigorous scientific enquiry and a quasi-experimental approach, to detect a tangible reality. The paradigm has been confirmed as post-positivism, using questionnaires and interviews to gather primary data, and unobtrusive research to collect secondary data, with the data analysed in a mainly statistical manner. It was recognised that there are limitations to the study, including the degree to which reliability and validity may be claimed. Finally, the ethics of the research was examined, confirming that anonymity and confidentially issues would be addressed in the study, with reassurances given to participants and stakeholders. The following chapter examines the collection and analysis of the primary questionnaire survey data and provides answers to the research question.

6 Collection and Analysis of Quantitative Data

6.0 Introduction

The purpose of this chapter is to analyse data collected through the questionnaire survey and explore answers to the research question, as well as validating the conceptual framework identified in Chapter 4. As first outlined in Chapter 1, the reason for this study is to investigate if construction schedule forecasting in reinforced concrete frame construction may be improved through the use of accurate performance data. In order to answer this question, the current practices and assumptions made when creating a schedule were explored. It was identified from both practice and a review of extant literature that schedules are prone to errors, with the memory bias of planners cited in the literature as a principal cause.

6.1 Summary of Data Collection

The primary data collection, as described in Chapter 5, was performed through a questionnaire survey. The SurveyMonkey website was selected to administer the questionnaire as it provides the ability to easily distribute access to the survey through the use of a hyperlink to the Survey Monkey website. The questionnaire was circulated to number of project managers, planners and consultants in the RC frame sector in June 2019, with a request to forward the questionnaire to other relevant, interested parties. The questionnaire survey was also circulated on social media (LinkedIn) and promoted on LinkedIn by the Chartered Institute of Building and the Association for Project Management, which led to an increased response rate. Due to the structure of the questionnaire and the requirement for skip logic and question streaming as outlined below, an enhanced subscription was paid to Survey Monkey for the Advantage Annual service for one year from April 2019 to April 2020, which was sufficient to cover the duration of the data collection between May and September 2019. The target audience was project managers and those involved in the measurement of progress and the development of construction schedules, and those stakeholders affected by construction progress.

According to Gray (2020), careful consideration must be taken when constructing a questionnaire in order to capture data that are valid, reliable and objective. It is therefore advisable that prior to issuing a questionnaire survey, a pilot survey is undertaken (Kaufmann, 2020; Gray, 2020), whilst Johnson and Christensen (2019) recommend that after a pilot study is performed, the questionnaire is revised and a second pilot test is undertaken to ensure the questionnaire operates correctly.

Drawing on this advice, the pilot questionnaire survey was designed and shared between five respondents, chosen as they fulfil the criteria of being both construction professionals and critical friends (McNiff, 2016) and their review highlighted a number of corrections required to the wording of questions and the layout and flow of the questionnaire. Four responses were received from the five pilot questionnaires issued, which provided sufficient criticism to enable improvement of the questionnaire. One reviewer commented that it was not clear if the responses required were to be the 'official company line' in terms of output rates, or if it was personal experience. This was clarified in the introduction to the questionnaire where it was stated that data from a recent project was required as opposed to standard company requirements.

Following the improvement of the questionnaire, it was piloted again to the four previous respondents and an additional two. The motivation for re-issuing the second pilot to the original four respondents was to ensure their criticism was interpreted and addressed correctly; the additional two respondents were chosen to gain an insight from people who had not viewed the questionnaire previously, as there was potential that they would identify any additional areas for improvement. All six participants returned comments from the second pilot study and it was deemed that the questionnaire was satisfactory.

6.2 Analysis of Responses

This section analyses the first five questions of the questionnaire to determine the demography of respondents, such as their age group, how long they have been working in the construction industry, their academic qualifications and the professional memberships they hold. The primary aim of this analysis is to verify the validity of the survey and to ensure that the survey is representative, credible, adequate and statistically reliable.

A summary of the respondents age group and experience is presented in Figure 6-1 below. It was found that at 52%, or 37 out of 70 respondents, the majority possess at least 11 years of experience, with five, or 7%, having relatively little experience of 1 year or less. In addition, a large majority of respondents (65%) were above the age of 35. This illustrates that participants possessed the maturity, experience and knowledge to provide informed responses to the questionnaire, as shown in Figure 6-1 below.

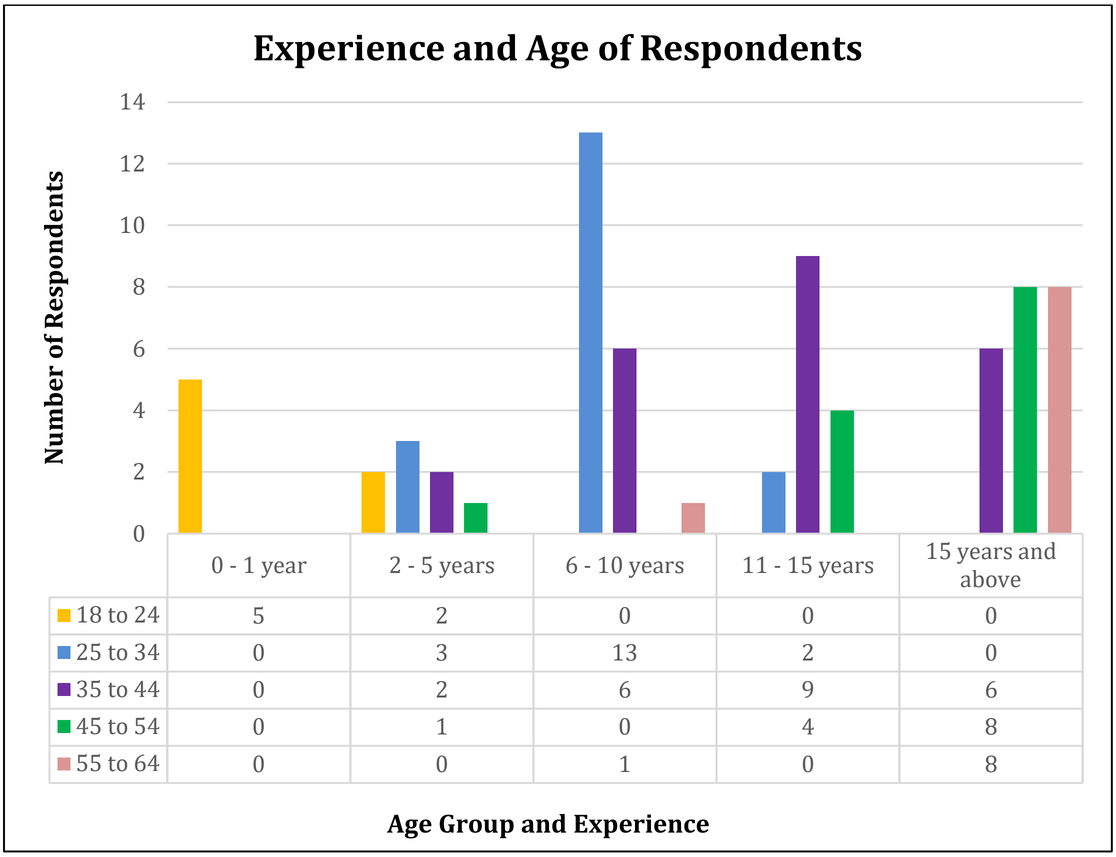


Figure 6-1. Respondents' Years of Experience and Age Groups

The most common respondents' occupation was found to be a Project Manager, at 23 out of 70 respondents, or 33%, followed by Quantity Surveyor and Planner at 13% and 11% respectively. The job title stated is important as it provides an indication of seniority and independence of decision making in the workplace, demonstrating that the respondents have the ability and knowledge to answer the questions posed later in the questionnaire. The results of the questionnaire also show that the highest level of level of academic qualification achieved by the majority of respondents was a Bachelor's Degree, with 51% of respondents attaining this award, and a further 29% holding a Masters' Degree or Doctorate. This result demonstrates that the majority of respondents hold a high standard of education and possess the capability to understand and respond to the questions posed in the survey.

Table 6-1 below provides a breakdown of professions and their experience in the industry. It is noted that, whilst only 11% of the respondents classified themselves as planners, project managers can also fulfil the planning role on their projects. Similarly, it is common for quantity surveyors to be engaged in the planning of projects, but retain their main function as quantity surveyors.

Table 6-1. Profession and Experience

Profession	Length of Experience in Construction					Grand Total
	0–1 yr.	2–5 yrs.	6–10 yrs.	11–15 yrs.	15 yrs. +	
Project Manager	2	3	5	8	5	23 (33%)
Quantity Surveyor	2	1	6			9 (13%)
Planner		2	2	2	2	8 (11%)
Engineer	1	1	3	1		6 (9%)
Contracts Manager			1		3	4 (6%)
Operations Director					3	3 (4%)
Planning Engineer		1			2	3 (4%)
Project Director					3	3 (4%)
BIM Manager			2			2 (3%)
Client Project Manager				2		2 (3%)
Construction Director					2	2 (3%)
Consultant Engineer			1		1	2 (3%)
Director					1	1 (1%)
Estimator				1		1 (1%)
Lecturer				1		1 (1%)
Grand Total	**5**	**8**	**20**	**15**	**22**	**70**

Question 5 enquired about professional memberships possessed by the participants, with the Institute of Civil Engineering (ICE) being the most popular professional body with participant membership at 12, or 18%, followed by the Royal Institute of Chartered Surveyors (RICS) at 10 (14%) and the Chartered Institute of Building (CIOB) at 9 (13%), as illustrated in Figure 6-2 below.

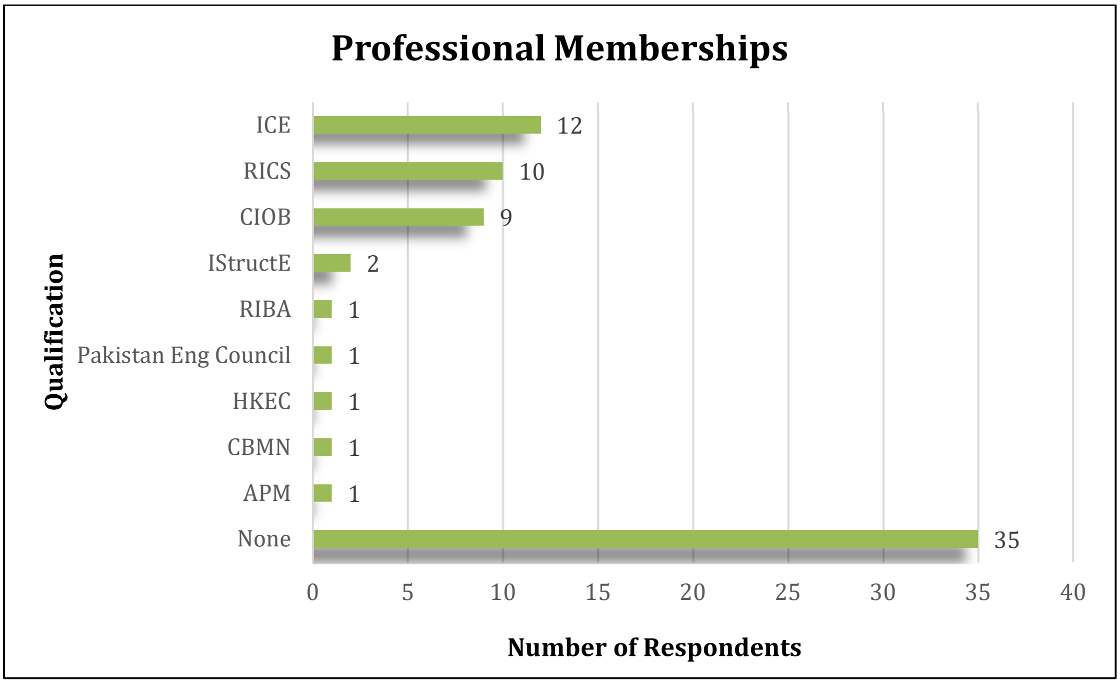


Figure 6-2. Professional Memberships

To be accepted as a member of the institutions indicated, candidates are assessed on their ability to perform professionally and ethically and to undertake their role rigorously and to a high standard. With 50% of questionnaire respondents stating that they possess such a professional membership, combined with a total of 80% possessing a university degree or greater, and 47% having more than 5 years' of industry experience, it may consequently be considered that participant knowledge and understanding, with regard to technical and operational questions, is satisfactory and further questionnaire responses are deemed credible as respondents possess the necessary knowledge and experience to provide valid questionnaire responses.

The results of the questionnaire survey are presented below in four sections, as follows:

1. Analysis of Progress Measurement
2. How Progress is Measured
3. Data Requirements for Progress Monitoring
4. Decision Making Informed by Knowledge

6.3 Analysis of Progress Measurement

The research problem was first identified in Chapter 1 and relates to the production of inaccurate construction schedules, where planned and actual task durations should be similar but in practice are not. In response, this research centres on the development of a process to improve construction schedule forecasting in reinforced concrete frames using historic performance data.

6.3.1 Scheduling References

One question common to both Group A and Group B was designed to interrogate what information would be used by the respondents to create a schedule, in order to investigate the methods employed when creating a schedule. The most popular response was to consult schedules from similar projects, with 66% choosing to use reference projects as a guide for future schedules. Whilst there is an argument that this may maintain or compound problems as planning errors are potentially carried from one schedule to the next, there is also an optimistic perspective that these respondents are at least comfortable with the concept of using historic output rates and potentially would be open to accepting RCF and a database of historic performance. Only 40% of participants would consult industry publications such as Spons (AECOM Ltd, 2016) to determine output rates when calculating schedule durations, whilst 54% indicated experience and intuition as the second-most popular means. These statistics demonstrate that construction schedules are compiled based more on intuition than evidence of historic performance.

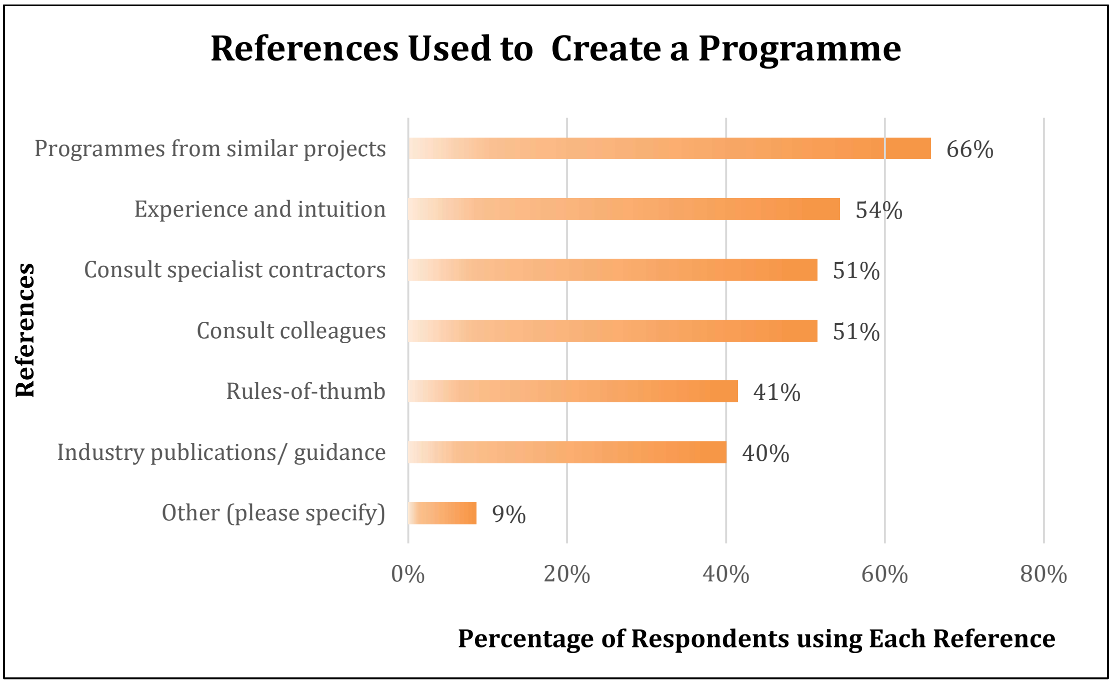


Figure 6-3. References used to create a schedule

A cross-tabulation of the results provides deeper analysis as illustrated in Table 6-2 below, which shows the methods employed to generate construction schedules and highlights that the largest group, those using schedules from other similar projects, heavily relies on data which is not evidence-based with 43% relying on experience and intuition, and 36% using rules-of-thumb. Table 6-2 also shows that, of those respondents using industry publications for guidance to create a schedule, 19% rely on rules of thumb and 17% rely on experience and intuition. This is concerning because even though there is verified data available from industry publications on which to base a schedule, and Figure 6.3 above shows that 60% do use these publications, the respondents remain reliant on unverified data and information to plan and schedule projects. It may be seen that between 19% and 36% of respondents rely on rules of thumb and between 17% and 43% rely on experience and intuition to create construction schedules. This finding strongly supports the industry experience that construction schedules are not fully evidence-based, rather a combination of previous schedules and consultation with experts, augmented by the extensive use of rules-of-thumb and intuition.

Table 6-2. References used to create construction schedules

	Consult schedules from similar projects	Experience and intuition	Consult specialist contractors	Consult colleagues	Rules-of-thumb	Industry publications and guidance	Other
Percentage of respondents using each reference	66%	54%	51%	51%	41%	40%	9%
Cross tabulation							
Consult schedules from other similar projects	0%	43%	44%	46%	36%	36%	9%
Experience and intuition	43%	0%	29%	30%	36%	17%	10%
Consult specialist contractors	44%	29%	0%	37%	21%	34%	9%
Consult colleagues	46%	30%	37%	0%	24%	31%	10%
Rules-of-thumb	36%	36%	21%	24%	0%	19%	9%
Industry publications and guidance	36%	17%	34%	31%	19%	0%	6%
Other	9%	10%	9%	10%	9%	6%	0%

6.4 How Progress is Measured

This section investigates how stakeholders assess progress during the construction of an RC frame (Group A), or, for those that do not assess progress as part of their role (Group B), how they believe it should be measured. Exploring the results of the literature review in Chapter 3, the aim of this section of the questionnaire was to investigate how progress is measured by practitioners. As identified in the methodology section in Chapter 5, the research design involves requesting information on the following areas to determine an answer to Research Question 1:

- Frequency of measurement
- Process of Measurement
- Effectiveness of Measurement

Gaining an understanding of these areas will help to establish the structure of the database, as similar data would need to be stored together and will in turn guide the format of the progress data collection form.

6.4.1 Frequency of Measurement

At 69%, or 38 out of 55, the majority of those that assesses progress (Group A) do so at least weekly, with 17 (31%) responding that progress assessment is undertaken daily and a further 15 (27%) a few times per week. Of those questionnaire participants that assess at least weekly, 36 out of 38 (94%), believe this frequency provides at least somewhat accurate results, whilst 37% (14) indicated that they believe it provides *very* or *extremely* accurate results.

It is notable that of those that measure less than weekly, a large proportion (76%, or 13 out of 17) believe that their methods of assessment are, at best, somewhat accurate, although the remaining participants (4, or 24%) believe that their results are *very accurate*. Many of those that measure progress with the least frequency, that is, less than once per month, have confidence in their measurements, as 33% (or 1 from 3) believe that their results are very accurate. Table 6-3 below shows the accuracy ranking for each frequency of measurement, based on the relative importance index (RII) of each.

Table 6-3. Relative Importance Index of Measurement Frequency and Accuracy

Frequency	Group A		Group B	
	RII	Accuracy Rank	RII	Accuracy Rank
A few times a month	47%	1	4%	5
About once a week	46%	2	23%	2
Once a month	45%	3	9%	3
Less than once a month	44%	4	0	7
A few times a week	43%	5	6%	4
Every day	38%	6	30%	1

The RII takes into consideration the ranking of the frequency of measurement by respondents, and is calculated by the following formula:

$$RII = \frac{\sum W}{A.N}$$ *Equation 6-1*

Where: W is the weighting given to each factor; A is the highest weight; and N is the number of responses.

This analysis indicates that the most accurate frequency method is a few times a month, closely followed by a frequency of about once a week. Therefore, considering the frequency of data collection of once per week is the second-highest accuracy ranking, it is deemed sufficient to collect productivity data at weekly intervals without increasing the workload burden for project managers and planners.

Of the group that do not measure progress (Group B), the vast majority, at 80%, feel progress should be measured at least weekly, which is greater than the 69% of those in Group A whom measure progress at this frequency. Therefore, it is clear that those who do not measure progress believe measurements should be undertaken more frequently. There is a strong statistical dependency between the measurement frequency and the perceived accuracy of the assessment method for Group A, as the Pearson Chi Square Test has established that there is a 99.979% probability that the variables are related. The Chi Square Test examines the likelihood that an observed distribution is due to chance. Also called a 'goodness of fit' statistic, it measures how closely the observed distribution of data fits with the distribution that is expected if the variables being tested are independent. The Chi Square Test is shown in Table 6-4 below.

Observed			
	Accuracy		
Frequency	Below 3	3+	Total
Below 2	10	7	17
2+	10	28	38
Total	20	35	55
Expected (if no difference)			
	Accuracy		
Frequency	Below 3	3+	Total
Below 2	6.18	10.82	17
2+	13.82	24.18	38
Total	20	35	55
Chi Square Test			
	P value =	0.020559199 (sig >95%)	
	α =	0.05	
Ho FALSE as P value < α, therefore **dependency established**			
	Probability of H1=	**99.98%**	

Table 6-4. Chi Square Test for Group A: Accuracy and Frequency

This is further confirmed by 47% (7 out of 15) of the Group B participants who indicated that progress should be measured every day, which is around 1½ times greater than the 31% of Group A that measure daily, an indication that Group B feels that the progress should be assessed at a greater frequency. It is noteworthy also that a significant majority (92%) of the Group B participants indicated that the progress being assessed was *somewhat accurate* at best, showing less faith in the accuracy than Group A.

Surprisingly, 8% (one Group B respondent) stated that progress in RC frames never needs to be measured. It is likely that the answer was either an error by the respondent or the question was misunderstood, as they have only one years' work experience and possess no formal education.

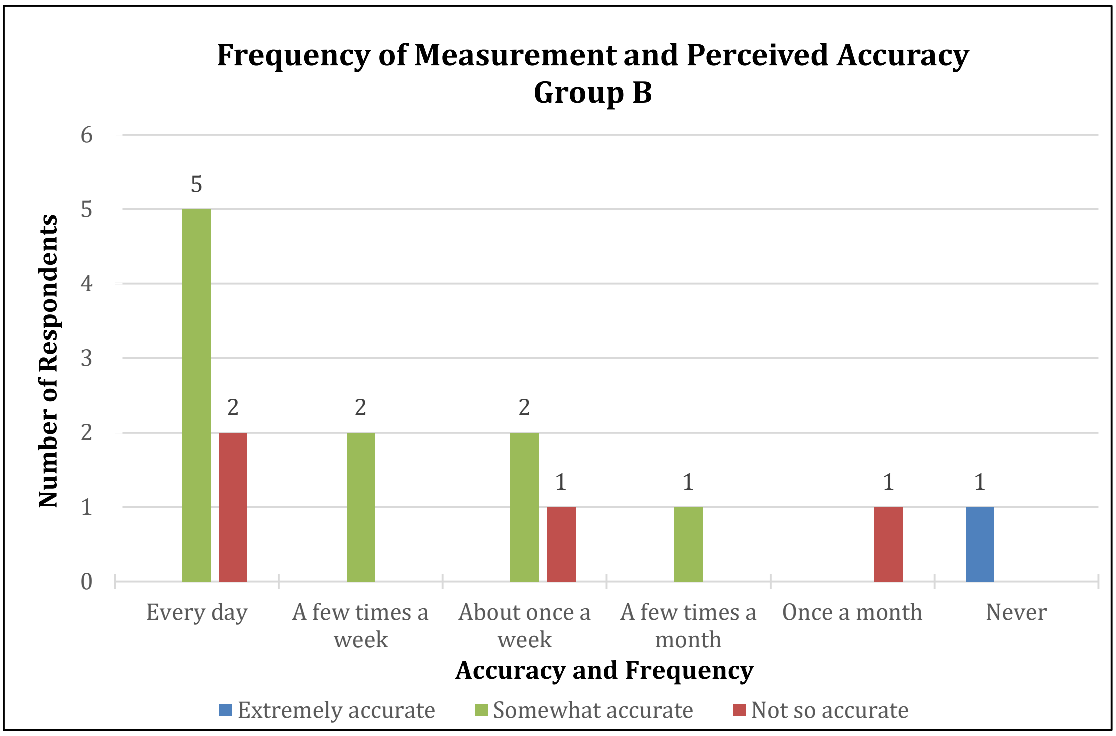


Figure 6-4. Group B's Measurement Frequency and Perceived Accuracy

It is evident from the 99.98% probability of dependency between the frequency and accuracy, and from the histogram in Figure 6-4, that to achieve the most accurate results progress should be measured frequently, at least once per week. This result is important as it permits structuring the progress data collection forms, which are necessary to populate a knowledge database.

6.4.2 Process of Measurement

This section is concerned with identifying how practitioners undertake progress measurement. For those that gather progress data (Group A), it is most commonly performed through a visual inspection (45%), with a further 38% using a combination of visual observations and physical measurements as their method for progress assessment, as shown in Figure 6-5. For Group B, the vast majority (92%) stated that progress should be assessed through a combination of observation and measurement.

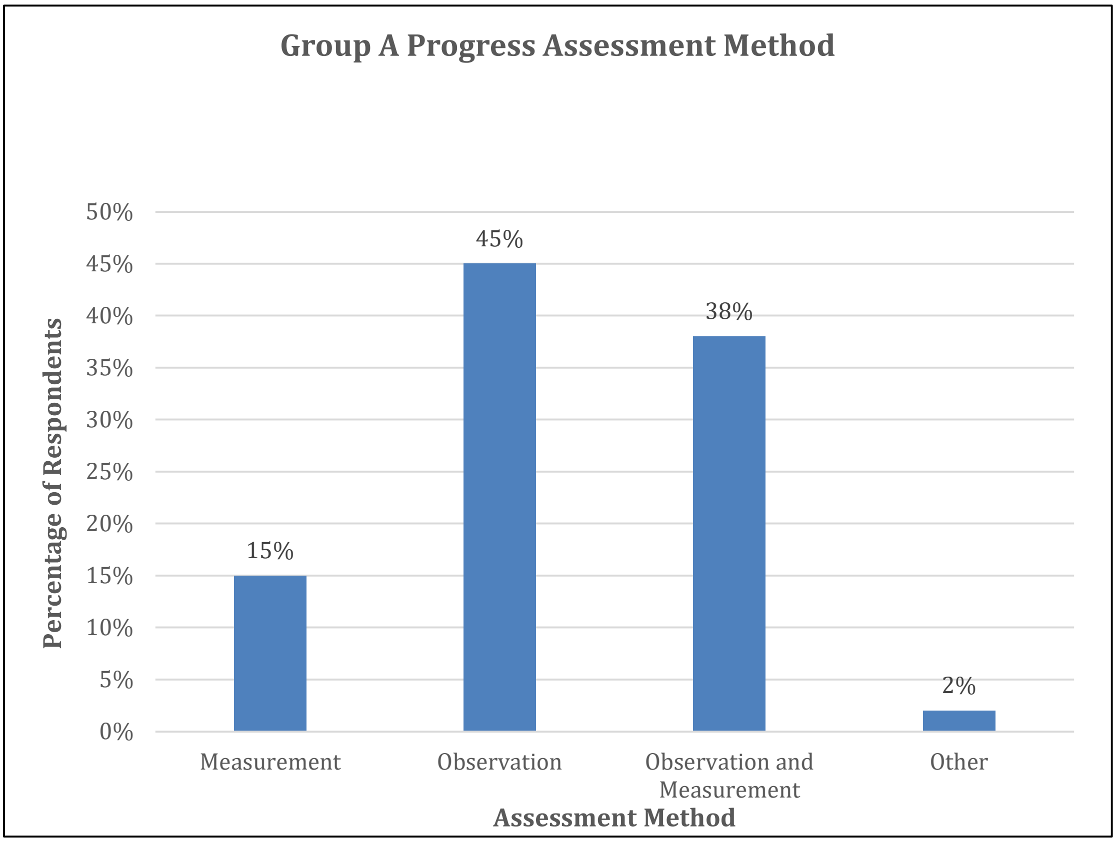


Figure 6-5. Group A Progress Assessment Method

Table 6-5 below shows that the practitioners using observations have the least faith in the accuracy of their process as no respondents indicated that their method of progress assessment is *extremely accurate* and only 7% indicating it is *very accurate*. In contrast, those whom use a combination of visual and physical measurements believe that their method of measurement is more accurate, with responses for this group showing that 4% believe the results obtained through this method are *extremely accurate*.

Table 6-5. Cross-Tabulation of Assessment Process and Perceived Accuracy

Measurement Process	Perceived Accuracy				
	Extremely accurate	Very accurate	Somewhat accurate	Not so accurate	Total
Observation	-	7%	33%	5.45%	46%
Measurement	2%	7%	5%	-	15%
Observation and Measurement	4%	15%	20%	-	38%
Other	-	2%	-	-	2%
Total	**6%**	**31%**	**58%**	**5%**	**100%**

In addition, a Pearson Chi Squared Test in Table 6-6 below shows there is a 99.99% probability that there is a relationship between the methods employed to assess progress and the accuracy of assessment.

Table 6-6. Chi Square Test for Group A: Accuracy and Method

Chi Square Test	
Ho: the two variables of accuracy and method of analysis are independent	
P value =	0.01238451 (sig >95%)
α =	0.05
Ho FALSE as P value < α, therefore **dependency established**	
Probability of H1=	**99.99%**

These results indicate that the majority of practitioners who assess progress use only visual means and do not store much faith in their measurement process. This is significant as it means that data may not always be accurate in the practitioners' opinion, therefore the output data collection form will need to be carefully phrased to request accurate data, as identified in Chapter 4.

6.4.3 Effectiveness of Measurement

The effectiveness of measurement is connected to how comprehensive the measurement of progress is undertaken; that is, how effective the process of measurement is, or is perceived to be. It was found that of the 55 participants that measure progress (Group A), 39 respondents, or 71%, believe that the assessment methods they employ are only 'somewhat' or 'not so effective', with the remaining 29% stating that they believe the methods are very or extremely effective. This is a notable result, as it shows the majority continue to use progress measurement methods even though they believe the methods have deficiencies, and are in part ineffective. The majority of the same group (57%) also stated that they use observation only as a means of assessing progress, an indicator that observation in isolation is not perceived by users to be an effective means of assessment. Table 6-7 below sets out these results.

Table 6-7. Group A Assessment Method, Perceived Accuracy and Effectiveness

		Method of Assessment				
Perceived Accuracy and Effectiveness		Measurement	Observation	Observation and Measurement	Other	Total
Not so Accurate	Somewhat effective		3 (5%)			3 (5%)
Somewhat Accurate	Very effective		3 (5%)	1 (2%)		4 (7%)
	Somewhat effective	3 (5%)	12 (22%)	7 (13%)		22 (40%)
	Not so effective		3 (5%)	3 (5%)		6 (10%)
Very Accurate	Extremely effective			2 (4%)		2 (4%)
	Very effective	2 (4%)	1 (2%)	3 (5%)	1 (2%)	7 (13%)
	Somewhat effective	2 (4%)	2 (4%)	3 (5%)		7 (13%)
	Not so effective		1 (2%)			1 (2%)
Extremely Accurate	Extremely effective	1 (2%)		1 (2%)		2 (4%)
	Very effective			1 (2%)		1 (2%)
Total Respondents		8 (15%)	25 (45%)	21 (38%)	1 (2%)	55 (100%

Where a combination of visual and physical measurements is used, 38% of Group A believe that the method is *Very* or *Extremely* Effective. This is in contrast with the group that use visual means only, as 16% believe the method is Very Effective, whilst no respondents believed that the method is Extremely Effective. Table 6-7 above illustrates the method of measurement contrasted with the perceived accuracy and effectiveness for Group A. The cross-tabulation of the perceived effectiveness and accuracy with the method of assessment in Table 6-7 show that the most frequently used method of assessment is observation, although most practitioners hold little faith in the accuracy or effectiveness of this means of progress assessment. The most accurate and effective means of progress assessment is to use both measurement and observation, as shown above in Table 6-7. This information supports the research by confirming that the process of progress assessment is flawed, the implication being that the data which assessments are based on are flawed. Therefore, it is imperative to create a database of historical performance to inform future planning and scheduling decisions. This is further explored in Chapter 9.

Surprisingly, Group B has more faith in Group A's processes than A does, with 67% stating that the measurement of progress is somewhat effective, and a considerable 33% holding the opinion that the means of measurement is very or extremely accurate, as shown in Figure 6-6 below.

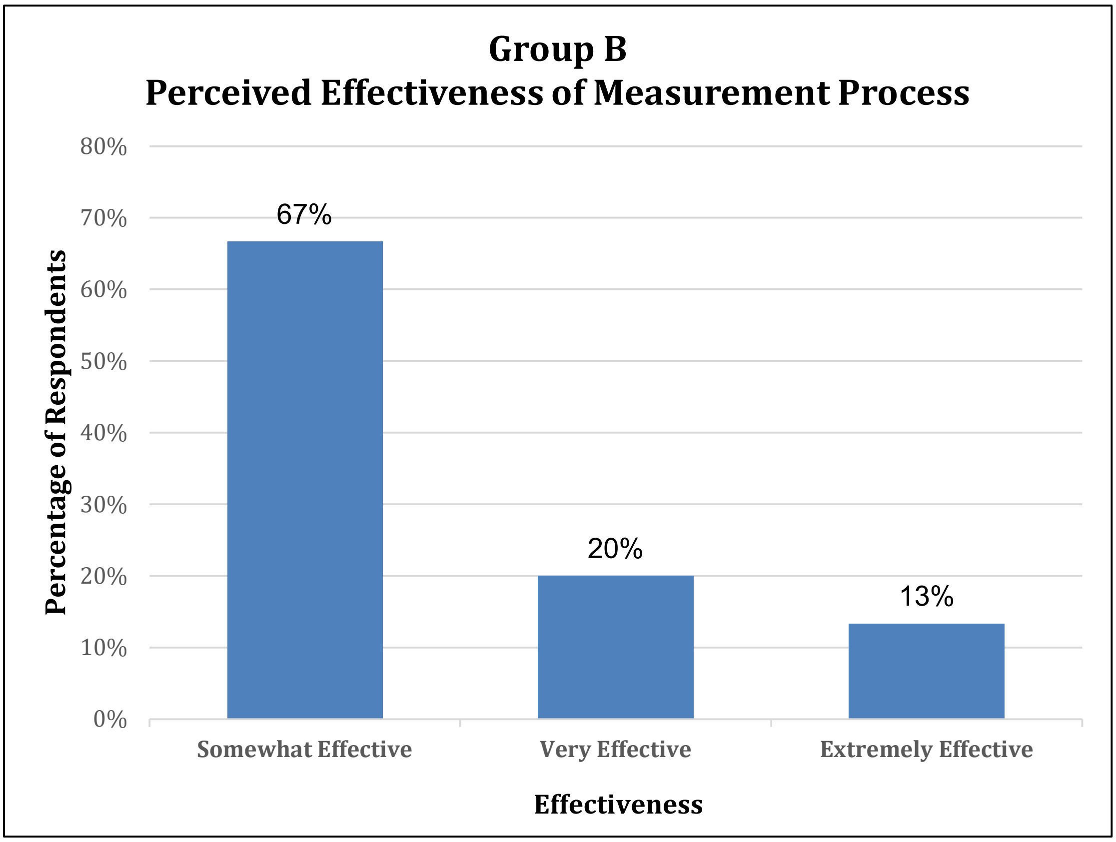


Figure 6-6. Group B Perceived Effectiveness in the Measurement Process

Significance testing on the combined responses of Group A and Group B shows there is a 99.99% probability that the accuracy of measurement and the effectiveness of assessment are not independent variables as indicated below in Table 6-8. A Chi

Square Test also demonstrates that there is a very high probability (99.999%) of an association between the method used and the accuracy of the progress assessment, refer to Table 6-9 below.

Table 6-8. Chi Square Test: Groups A and B: Accuracy and Effectiveness

Chi Square Test	
P value =	3.217E-05 (sig >95%)
α =	0.05
Ho FALSE as P value < α, therefore dependency established	
Probability of H1=	**99.99%**

Table 6-9. Chi Square Test: Groups A and B: Method and Effectiveness

Chi Square Test	
P value =	6.391E-09 (sig >95%)
α =	0.05
Ho FALSE as P value < α, therefore dependency established	
Probability of H1=	**99.99%**

6.5 Data Requirements for Progress Monitoring

The data required for progress monitoring is critical to this research as it investigates how practitioners assess and measure progress, what data stakeholders use to measure progress on their projects and how they see particular tasks influencing progress. This section also explores how information and knowledge are produced in practice, providing an understanding of what data is available and whether it could be used to inform project durations in the future. The main areas this section examines relate to the following:

- Types of data used to measure progress
- Accuracy of progress assessment
- Task influence on progress

Group A stakeholders, that is, those undertaking progress measurement, were asked additional questions regarding their assessment of typical performance achieved for specific elements of the construction, in particular formwork and reinforcement outputs, and the average time taken to complete one floor slab cycle.

6.5.1 Type of Data

Those that assess progress were questioned on the type of data they consult to measure progress, with Question 17 being an open-ended question designed to permit participants the freedom to expand on their responses. The replies received had a high degree of consistency, with almost all (96%) mentioning the words *concrete*, *slabs* or *everything*, indicating that most consider the casting of the floor slab as a measure of progress.

Interestingly, of those that chose ‘concrete’ as the most important criterion to assess progress, 60% believe that their methods are only ‘somewhat accurate’. The inference here is that the most popular choice of data to measure progress is, at best, somewhat accurate.

A number of respondents (13 out of 55, or 23%) stated that *formwork* is assessed during their progress measurement exercise and 9 respondents, or 16%, specifically mentioned reinforcement installation. This correlates with Chapter 2, where it was found that slab cycle duration, followed by formwork and reinforcement installation were three of the most critical elements for consideration of progress in RC Frame construction. Refer to Figure 6-7 below, which illustrates the considerations made when progress is being assessed on site.

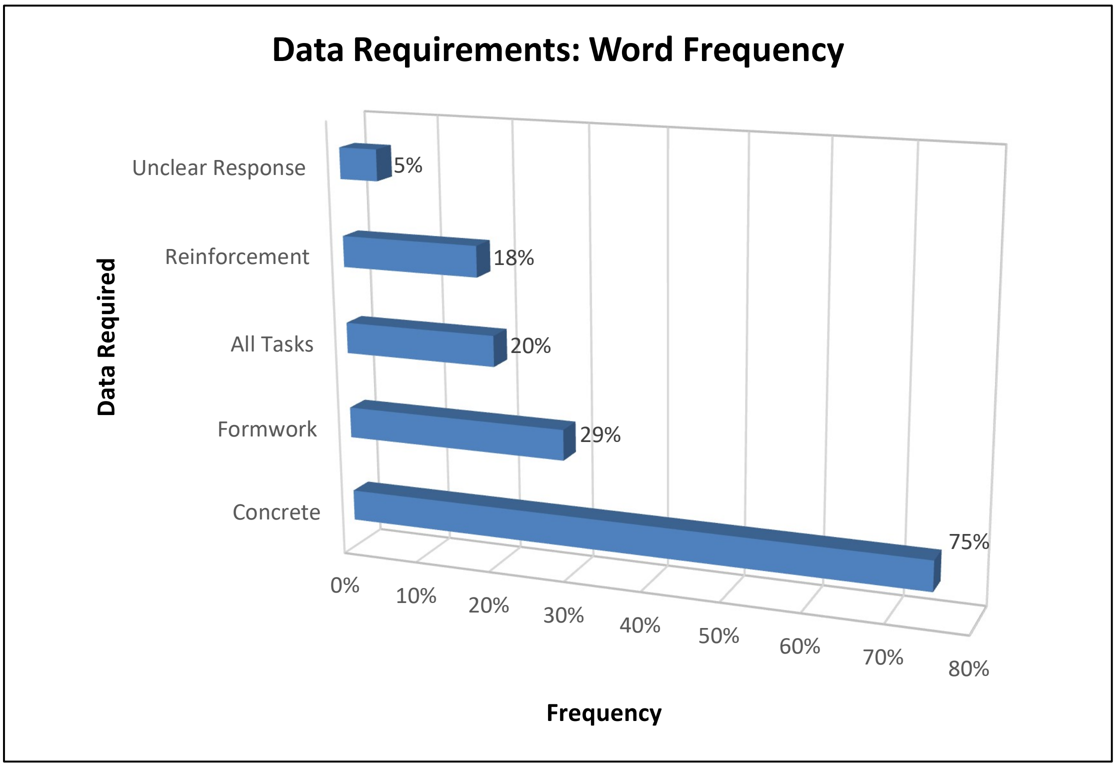


Figure 6-7. Questionnaire Question 17: Data Chosen to Measure Progress

The findings here are relevant to this research as it is critical to identify what criteria are important when progress is being measured on site, as it enables the collection of relevant project reference data to populate the knowledge database.

6.5.2 Rates of Output

Rates of output have been discussed in Chapter 2 above, and with regard to the reinforcement, formwork and slab cycle times, it was highlighted that estimates of output fluctuate. Therefore, knowledge of these three variables is fundamental to enable accurate schedule forecasting. As a consequence, actual site performance measurement is important to the creation of reference data and information which will inform future planning decisions. In relation to the level of formwork output, respondents indicated an average output of 11.8m^2 per day per carpenter. There was a significant range of results, however, with the lowest value 6m^2/day/carpenter and the highest value 20m^2/day/carpenter. Notwithstanding this range, the most frequent response given, or the mode, was found to be 12m^2/carpenter/day. Similar to the carpentry output responses, the steel fixing output indicated by questionnaire respondents varies greatly, with the average quantity installed selected as 982kg/steel fixer/day. The range between the highest and lowest daily estimate was also significant, with the lowest at 750kg/day and the highest given as 1400kg/steel fixer/day and the most common output rate selected, the mode, was 1000kg/steel fixer/day.

The slab cycle time is the length of time to complete each successive slab pour, that is, the construction of the walls and columns supporting the slab, erection of falsework and formwork, installation of reinforcement and placing concrete. The questionnaire responses indicated that the highest estimate of the slab cycle time was 25 days and the lowest 5 days, however, the average cycle time was found to be 12 days, as was the mode. Table 6-10 below shows the results of the questionnaire, for Groups A and B combined.

Table 6-10. Estimated rates of output based on questionnaire results

	Formwork Output (m^2/ carpenter / day)	Reinforcement Output (kg / steel fixer / day)	Slab Cycle Time (days / cycle)
Mean	11.829	982.357	11.514
Maximum	20	1400	25
Minimum	6	750	5
Mode	12	1000	12
Median	12	1000	12

6.5.3 Accuracy of Measurement

The accuracy of measurement relates to how accurately construction progress is measured on site. Questionnaire response Group A have a reasonably high level of confidence in the accuracy of the methods they use to measure progress, highlighted by the 94% that indicated they believe their methods are *somewhat*, *very* or *extremely accurate*, as shown in Figure 6-8 below. The remaining 6% believing that their methods of assessment are not so accurate. This contrasts with those that do not measure progress (Group B), where 33% are critical of Group A's methods of assessment, believing that those measuring progress are not accurate.

Interestingly, those using visual means to evaluate progress do not have much faith in their method, as 72% of these people believe their method is only somewhat accurate, with a further 12% indicating that their method is not so accurate. In addition, 30% of those that use visual inspection also rely on feeling or instinct when estimating progress. This indicates an acknowledgement among those that use visual means only to assess progress that their method is inaccurate to some degree. This sentiment was endorsed by two interviewees, who stated that visual inspections will give a 'rough estimate' or an 'indication' only of the progress.

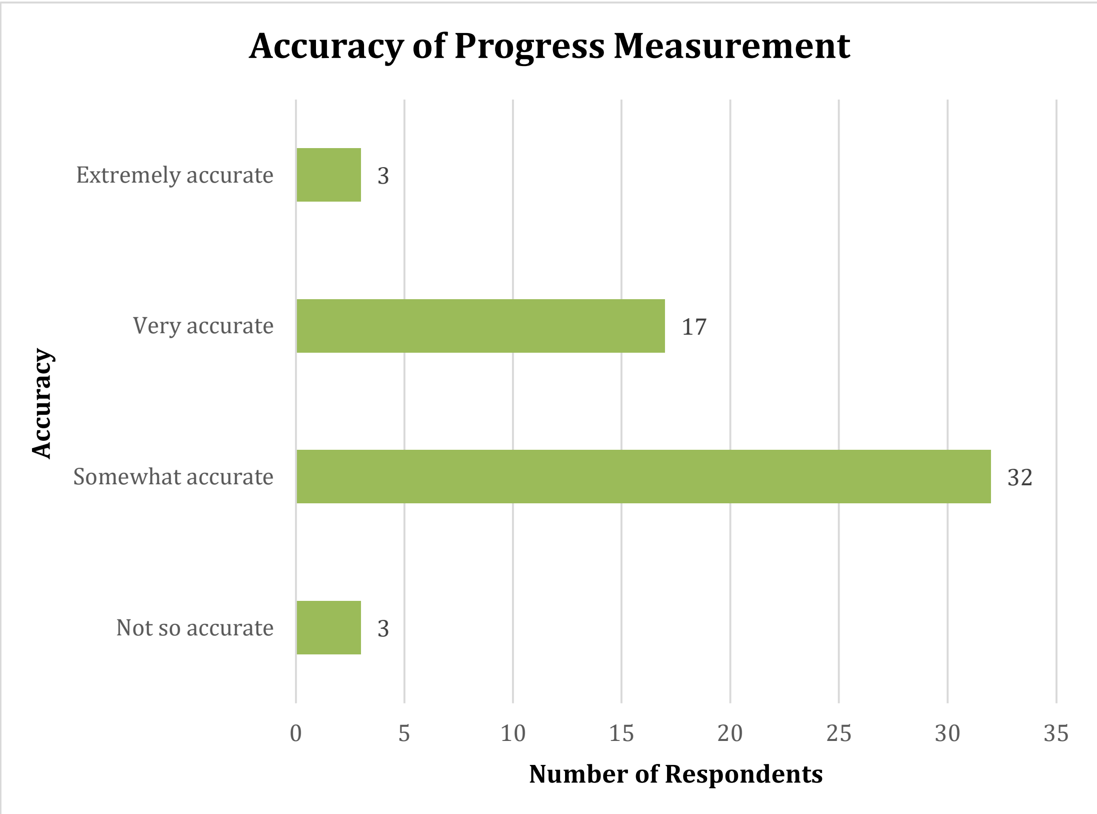


Figure 6-8. Accuracy of Progress Measurement

In contrast, of the 15% that rely on measurement to perform a calculation to determine progress, a large majority (63%) believe that their chosen method is *very accurate* or *extremely accurate*. For those that utilise a combination of observation and measurement methods, 38% believe that their method is *somewhat*, *very* or *extremely accurate*. It is therefore held that visual inspections have a moderating influence on physical measurements of progress, leading to the conclusion that the most accurate means to determine progress is to undertake a measurement exercise rather than using visual methods.

6.5.4 Task Influence on Progress

This section relates to the amount of influence a particular task is perceived to exert on progress. The majority of respondents (69% for Group A and 75% for Group B) indicated that the concrete placed is the most important consideration when assessing progress. This is followed by most people (29% of Group A and 45% of Group B) believing that the installation of reinforcement is the second most important consideration. For both Group A and B, the erection of formwork was viewed to be the fourth most important factor. With reference to the erection of formwork, both groups selected it as the third most important consideration. Table 6-11 below shows the ranking of various factors considered when measuring progress.

Table 6-11. Ranking of various factors in progress measurement

		Rank				
		1 (High)	2	3	4	5 (Low)
Group A	Concrete	**69%**	24%	2%	4%	2%
	Reinforcement	6%	**29%**	27%	22%	16%
	Formwork	8%	18%	**29%**	29%	16%
	Vertical Members	0%	1%	14%	**18%**	18%
	Feeling or Instinct	18%	27%	14%	10%	**31%**
Group B	Concrete	**75%**	17%	0%	8%	0%
	Reinforcement	8%	**42%**	33%	8%	8%
	Formwork	17%	25%	**33%**	17%	8%
	Vertical Members	0%	8%	25%	**50%**	17%
	Feeling or Instinct	0%	8%	8%	17%	**67%**

It was surprising to discover that 18% of those assessing progress believe that trusting their feeling or instinct is the most important factor to consider when calculating or measuring progress. Those with significant experience in the industry (15 years or more) were found to be more comfortable with using their intuition when they assess progress, as 37% believe that their instinct is the most important factor. This reliance on feeling or instinct indicates that the assessment of progress is an estimation only and therefore prone to inaccuracy, as found in the literature where poor judgement is described as a root cause of project failure (Flyvbjerg, et al., 2009; Chan & Kumaraswamy, 1997; Pinto & Mantel, 1990). 45% of Group A believes that feeling or instinct is ranked as either the most important or the second most important consideration when assessing progress. This is in contrast to 8% of the Group B respondents, a clear indication that those not measuring progress believe that feeling or instinct are not significant considerations for progress assessment, with 2 out of 3 (67%) stating that feeling or instinct are the lowest-ranking factors in their assessment of progress.

6.6 Decision Making Informed by Knowledge

This aspect of the research is designed to explore the benefits, or perceived benefits, to be gained from the use of historic performance data, with questionnaire participants requested to explain how they would create a schedule for a concrete frame, illustrating what information was deemed to be the most useful. Respondents were also invited to give an opinion on the influence of the progress of the concrete frame on the overall project progress, providing data on the perceived influence the reinforced concrete frame has overall.

6.6.1 Influence of Concrete Frames on Overall Project Progress

Participants in this research were questioned on the degree of influence they feel the RC frame has on the overall project progress. The purpose of this question is to explore the argument that the concrete frame is critical to the progress of the overall project, reinforcing the argument in the identification of the problem in Section 2.1 above where it was outlined that concrete frames are a critical part of the industry landscape and have a significant influence on the overall progress of projects.

Almost all (96%) of questionnaire respondents consider that the progress of the RC frame has a very strong or strong influence on overall project progress, as illustrated in Figure 6-9 below. The results indicate there is a belief that progress of the concrete frame is a critical success factor in overall project progress. There was some distinction between Group A and B respondents, with a slightly lower proportion of those that do not measure progress (75%) believing that the concrete frame has very strong, or strong, influence on overall project progress.

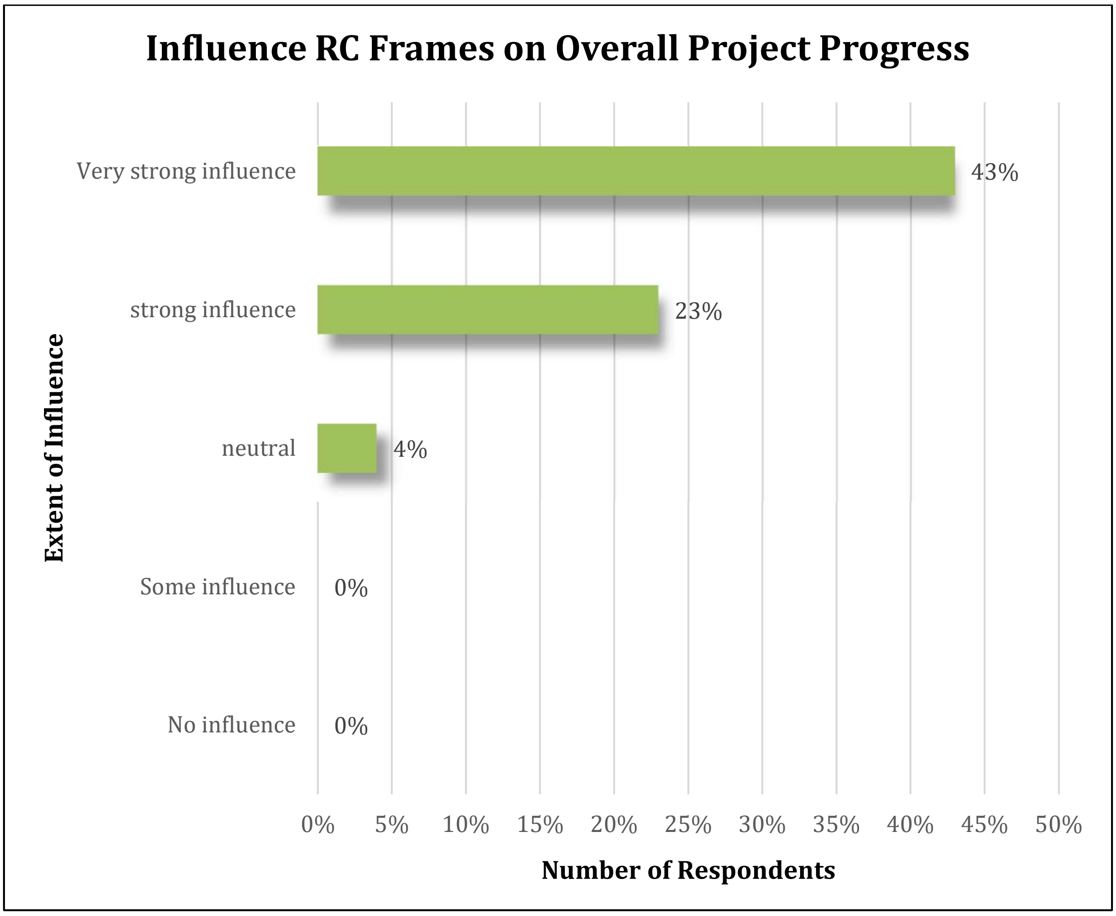


Figure 6-9. Influence of RC Frames on Overall Project

6.6.2 Past Performance Data

The questionnaire respondents were all asked to indicate if they believed that knowledge of past performance could increase the accuracy of future schedules. The responses were quite positive, with most indicating they believed knowledge of past performance would increase schedule accuracy as shown below in Figure 6-10.

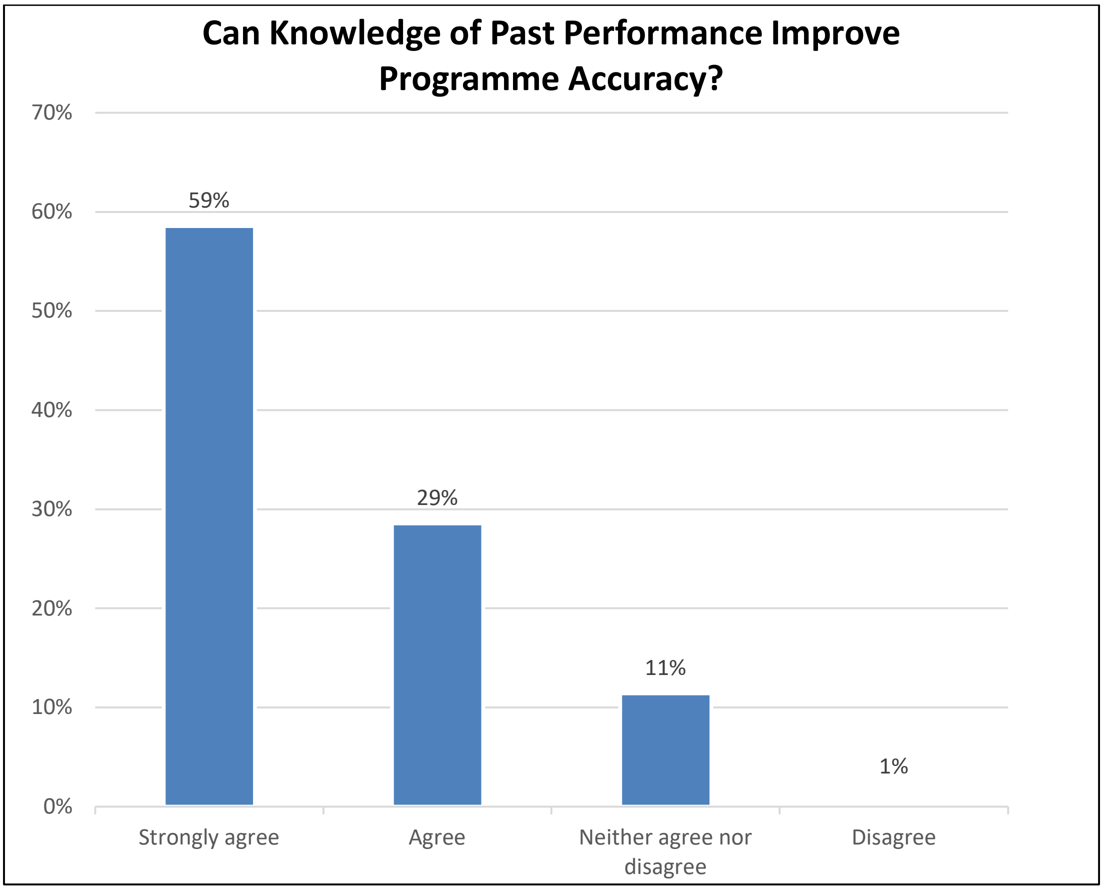


Figure 6-10. Knowledge of Past Performance

This section of the questionnaire survey was designed to explore the opinions of participants in how they can use knowledge gained from past experiences to inform future planning decisions. This is the broad basis of RCF which underpins this research. All participants in the study indicated that they believe that scheduling accuracy can be enhanced through knowledge gained from past performance, which is at the heart of RCF. It is encouraging that all respondents recognise that there is merit in the use of historic data to inform future planning decisions.

6.7 Chapter Summary

The purpose of this chapter is to investigate productivity on RC frame construction projects, addressing Research Objective 3: *To investigate construction site productivity* as identified in Chapter 1. The data gathered from the primary research has been presented and analysed to provide answers in response to the industry problem of how the creation of inaccurate construction schedules can be overcome. The main finding drawn from the questionnaire survey is the lack of evidence-based data used by practitioners to inform their scheduling decisions, where there was an acknowledgement that their production rates and duration estimates do not provide the greatest accuracy.

The main finding drawn from the questionnaire survey is the lack of evidence-based data used by practitioners to inform their scheduling decisions, despite an acknowledgement that their production rates and duration estimates do not provide the greatest accuracy. The survey found that monitoring was predominately performed through visual inspections of the works, although respondents did not consider this to be the most effective method with the results showing that a combination of visual inspections and physical measurement being the most effective at capturing progress. This is concerning as it shows that practitioners continue to assess progress visually, even though they acknowledge this method is sub-optimal. The data collected indicates that the majority of progress measurement is undertaken at least a few times per week, with about 1 in 3 monitoring progress daily. However, it was found that 24% of respondents that measure less than weekly believe that they measure progress with accuracy.

This monitoring was predominately performed through visual inspection of the works, although this was not seen as the most effective method. A combination of visual inspection and physical measurement were judged by questionnaire respondents as the most effective method to use, with 38% reporting that they use this method believing it is very or extremely effective. The frequency of measurement must be sufficient to capture the required data and the harvesting of this data and its distillation into a database should have a weekly frequency, as this captures 69% of respondents without any additional monitoring burden on project staff. Therefore, the most accurate and effective method to measure progress is to collect it weekly, using a combination of visual inspection and physical measurement. This conclusion will inform the frequency of use of the data collection tool, including embedded text prompting the user to enter data on a weekly frequency. This will maintain a structure to the collection of progress data, allowing comparison of performance to be undertaken consistently within a project and across projects. Establishing a frequency and method to achieve the most accurate and effective progress data also informs the structure of the knowledge database as well as controlling the volume of data collected and entered.8

Ten questions were included in the questionnaire to determine what type of data practitioners require to measure progress. Understanding the data practitioners use to monitor schedules provides the basis for the data collection algorithm which will inform the knowledge database. Comprising of questions regarding the measurement of data, typical outputs for carpenters and steel fixers and slab cycle times, the questionnaire also enquired about the accuracy of the progress measurements performed, the contribution of various tasks to the practitioner's assessment of progress and the references and resources drawn upon when creating a schedule.

An assessment of the number of concrete floor slab pours is the most common means to measure progress, although this is not the optimum method because it is a measure of one single element, rather than assessing the rate of installation of formwork and reinforcement. Despite this shortcoming, it is considered sufficient by industry for a high-level assessment, with formwork and reinforcement assessment providing a more accurate measure of progress. Practitioners felt reasonably confident that their methods were accurate, although those that use visual means only believed this method is not so accurate, yet they continue to use it. This leads to the conclusion that visual observations and physical measurement of formwork and reinforcement productivity will provide the most accurate means of measuring progress, with the slab cycle time also considered significant as it illustrates the overlap in the use of formwork and reinforcement resources.

The questionnaire survey also enquired if practitioners would be open to having their decision-making processes informed by the knowledge gained from performance data. Answering this question is fundamental to establishing whether or not an algorithm would be useful, as if the end-users do not have faith in the premise that historic data can assist in making scheduling decisions the tool will be difficult to implement, and likely destined for failure. This is not the case, however, as all questionnaire respondents (100%) stated that they believed historic performance is a suitable predictor of the future.

In conclusion, the questionnaire survey data collected indicates that the optimum frequency of progress data collection is weekly, and this should consist of a physical measurement and visual observation of the works, in particular for formwork and reinforcement installation. Practitioners, according to those surveyed in the questionnaire, would be comfortable using historic data to inform future construction schedules.

The following chapter presents an analysis of historic data from the review of six schedules, exploring what the data means and where this data can be used to create a planning knowledge database to determine progress durations.

7 Unobstructive Research

7.0 Introduction

The purpose of this chapter is to analyse data from a number of schedules, in order to understand the progress achieved during the lifecycle of a project. Five criteria were used to select six schedules, consisting of four schedules from within the researcher's organization and a further two from external sources which were provided by interviewees. In order to preserve anonymity and not compromise sensitive commercial information, the six schedules were designated by letters A to F, refer to Table 7-1 below. The schedules were examined with a view to providing the following:

- data and information on the creation of a planning reference database
- answer the research question

Table 7-1 Projects selected for analysis

	Project Reference					
	A	B	C	D	E	F
Overall Tender Duration (days)	432	237	179	390	345	441
Critical Schedule Improvement (days)	0	0	0	0	-56	0
Height of Concrete Frame, in storeys	14	6	8	52	35	10
Area of Formwork (m2)	27550	8550	12500	42000	17500	24000
Volume of concrete (m3)	9325	2505	4255	11790	5355	8400
Reinforcement (T)	2322	1102	1320	4325	1445	1718

7.1 Schedule Selection

Six construction schedules were selected as described above, where four internal and two external schedules were chosen from a long list of 36. The data collection was performed by compiling productivity details, as described in Chapter 4, from six completed projects, selected through consideration of four main criteria, including the type and nature of project, the planned construction schedule sequence and the Project Managers' and Clients' receptiveness to the study. The construction schedules exhibited differences in the way projects are planned and how progress was recorded. For the internal schedules, there were detailed work breakdown schedules (WBS) evident, whilst the two external schedules were at a slightly higher level and contained less detail in the WBS. The schedules were reviewed under a number of headings to allow a comparison of the data as illustrated in Table 7-2, including the following:

- Schedule duration
- Frequency of measurement
- Planned and actual duration of formwork, reinforcement installation times
- Planned and actual duration of slab cycle times

Table 7-2. Schedules selected for analysis

	Project Reference					
	A	B	C	D	E	F
Note: Negative figures indicate a schedule improvement						
Height of Concrete Frame, in storeys	14	6	8	48	35	10
Area of Formwork (m2)	27550	8548	5320	22000	17790	30000
Volume of concrete (m3)	9325	2505	4255	11790	5355	8400
Reinforcement (T)	1446	448	212	1194	560	1525
Overall Tender Duration	432	237	179	390	345	441
Actual Construction Duration	520	255	200	405	289	599
Critical Schedule Delay	**88**	**18**	**21**	**15**	**-56**	**158**
Frequency of Progress Measurement	7	14	7	7	14	7
Formwork						
Planned Duration of Formwork	190	148	115	275	200	120
Actual Duration of Formwork	203	148	123	288	194	130
Critical Delay to Formwork	**13**	**0**	**8**	**13**	**-6**	**10**
Reinforcement						
Planned Duration of Reinforcement	175	130	98	235	120	84
Actual Duration of Reinforcement	184	125	98	229	118	85
Critical Delay to Reinforcement	**9**	**-5**	**0**	**-6**	**-2**	**1**
Slab Cycle Time						
Planned Average Slab Cycle Time	12	10	10	6	7	8
Actual Average Slab Cycle Time	9	10	10	6	7	7
Difference in Slab Cycle Time	**-3**	**0**	**0**	**0**	**0**	**-1**

It would be normal practice in the industry to compare projects based on monetary value, however this was not possible as permission was not granted to publish commercial information in this research.

7.2 How Progress is Measured

With regard to progress measurement as outlined in Section 2.2.4 above, it is not straightforward to determine from schedule analysis *how* progress was measured, as only the results of progress measurement are indicated on schedules and project reports. As a consequence, analysis of the schedule alone cannot establish how the data was collected or what data was collected, because the schedules show the results of the measured progress against each task rather than the means to assess and gather progress data. This is also the case for the project documentation, where the progress is reported, rather than the means used to measure the progress.

For four of the schedules reviewed (67%), progress was assessed weekly, with the remaining two (33%) assessed every two weeks. This supports the results of the questionnaire, where it was found that 69% measure progress at least weekly. It is also recognised that progress may be measured at a greater frequency than shown on a schedule. For example, site management would usually assess progress daily but only report formally the findings weekly or fortnightly.

It is not possible to fully understand the assessment process used on site, as this information is not available. For example, physical measurement or observation, or a combination of both, may have been used to determine progress, however this cannot be interrogated as the data is not available. It is considered, however, that the methods used are effective as the progress is recorded successfully for all tasks in the six schedules reviewed and therefore is credible for use in this research.

7.3 Measured Data

Having established in Section 2.2 above that the main components of RC frame construction are related to formwork, reinforcement and slab cycle times, the construction schedules were analysed for variance in the duration and task output rates for the three components of formwork, reinforcement and slab cycle durations, comparing what was planned with what was actually achieved. This was then compared to the questionnaire results, identifying the differences and similarities.

7.3.1 Construction Schedule Durations

The overall durations of the six construction schedules under review were considered and, with reference to Table 7 2 above, it was found from the analyses that 5 out of 6, or 83%, of projects were completed late, with the average being 41 days late, or just over 8 working weeks. The reasons for the extended durations were multiple, however the majority were caused by delays from preceding contractors, with piling, groundwater and excavation delays indicated as the most common causes. The durations for slab cycle times, formwork and reinforcement installation were analysed across the six schedules, at both the planned and completion stages. The results demonstrate that, on average, the formwork was completed 6 days later than planned and the duration was greater than anticipated in 2 out of the six, or 33% of projects. With regard to reinforcement, it was completed on average one day earlier than planned, albeit with a greater duration than anticipated in 33% of projects.

In contrast, it was noted that although the reinforcement and formwork may have been delayed in some instances, the planned slab cycle time was achieved for 67% projects. This was accomplished in these projects through an increased overlap between the installation of vertical members, formwork and reinforcement tasks. The average slab cycle time was found to be 8 days, closely correlating with the 10 days indicated by the questionnaire results.

7.3.2 Output Rates

For the six schedules examined, rich data was available for the formwork and reinforcement installation, in particular the output rates as defined in Section 2.2.3 above. This permitted close analysis of the productivity output rates for carpenters and steel fixers in terms what was planned at tender stage and the actual output rates achieved in the construction stage, including planned and actual data and information on the following:

- Quantities of formwork, in square metres
- Quantities of reinforcement, in tonnes or kilogrammes
- Numbers of carpenters and steel fixers
- Duration of formwork and reinforcement installation in days

The above was determined from three sources, namely the tender schedule, the as-constructed (or as-built) schedule and other project documentation. The supporting project documentation included tender information from the planning stage, such as geometric details of the slab pour areas, concrete volumes, soffit heights, and planning information such as labour quantities, outputs and sequence drawings. This was complimented by site documentation which included progress reports, short-term planning spreadsheets and labour allocation sheets.

Analysis of the project information and data is crucial, as it provides details of the outputs planned at tender stage and achieved on site during project execution. Pearson's Chi Square test has also been performed on the relationship between the questionnaire results and the results from the planned and actual outputs to establish if there is any association between the sets of data. The findings of this analysis are then used to determine if they are suitable for inclusion in the development of both the knowledge database and duration prediction algorithms, as output rates form the basis of the calculation for task duration.

Carpenters

There are clear differences between the tender assumptions made regarding expected carpenter outputs and what was actually delivered on site. This confirms the claim made in Chapter 2 that the inaccuracy in construction schedules is due to a lack of understanding of onsite performance and output rates. The planned output rates for all six projects was found to be almost $10m^2$ of formwork erected per carpenter per day, which aligns closely with the results of the questionnaire where the mean output rate was found to be $12m^2$ of formwork per carpenter per day. Both of these values are greater than what was actually achieved in project delivery, as the average output was almost $9m^2$/carpenter/day, equating to 8.8% lower productivity per carpenter than expected at tender stage.

- Project F presented the largest difference in output, suffering from an 8% reduction.
- Project D exhibited a 4.5% drop in output and, although the Project D formwork was completed 13 days (or 5%) early than the planned duration, additional labour resource of 13% was provided to complete the formwork to achieve this earlier completion time.
- In contrast, Project B was the only project from the six reviewed that was executed as intended, achieving the planned output rates with the planned quantity of carpenters, completing the formwork erection on time.
- Project E completed the formwork 6 days early, due to an increase in output by 3%. The findings are shown below in Table 7-3.

Table 7-3. Planned and Actual Carpentry Outputs

		A	B	C	D		F
Planned	Area of formwork (constant) (m2)	27550	8548	5320	22000	17790	30000
	Quantity of Carpenters	14	6	6	8	10	22
	Planned Duration of Formwork (days)	190	148	115	275	200	120
	Planned Output (m2/carp/day)	10.357	9.626	7.710	10.000	8.895	11.364
Actual	Actual Duration of Formwork (days)	203	148	123	288	194	130
	Actual Output (m2/carp/day)	9.694	9.626	7.209	9.549	9.170	10.490
Differences	Difference in Duration (days)	13	0	8	13	-6	10
		7%	0%	7%	5%	-3%	8%
	Difference in Output (m2/carp/day)	-0.663	0.000	-0.501	-0.451	0.275	-0.874
		-6.40%	0.00%	-6.50%	-4.51%	3.09%	-7.70%

Note: Negative values indicate a decrease in value, which is an improvement on the planned value.

Pearson's Chi Square Tests of independence have been performed on the relationship between the questionnaire results and the results from the schedule analysis regarding planned and actual outputs. The Chi Square Test was selected as it measures how expectations, or questionnaire data, compare with observed data, or the actual schedule performance and is suited to data sets of the magnitude used in this research. It was found that there is a probability of 83.90% of no relationship existing between the questionnaire values for formwork output and the planned values as found in the six schedules, as shown in

Table **7-4** below. This indicates that the planned values have no relationship to what practitioners believe the outputs should be, confirming the gap in practice found in Section 2.4.

Table 7-4. Chi Square Tests for Formwork Output

Chi Square Test Results	
Questionnaire and Predicted Values for Formwork Output	
P value =	16.096%
α =	0.05
Ho TRUE as P value > α, therefore independent variables	
Probability of H1=	**83.90%**
Questionnaire and Achieved Values for Formwork Output	
P value =	0.0036%
α =	0.05
Ho FALSE as P value < α, therefore dependency established	
Probability of H1=	**99.96%**

The Chi Square test was also performed on the achieved values for the formwork from the schedule analysis and compared to the results from the questionnaire. In this instance, as illustrated in Table 7-4 above, it was found that there was a 99.96% probability of there being a relationship between the variables, an indication that there is a relationship between the actual outputs and the outputs practitioners perceive there to be. The questionnaire and schedule analysis results are therefore considered to be valid and suitable for inclusion in the database.

Steel Fixers

In contrast to the formwork results, there was less variation between the output levels planned at tender stage and what was actually achieved in practice. Across the six projects, there was a planned output rate of 923kg of reinforcement installed by each steel fixer per day which, at 74kg difference, was reasonably close to the actual rate achieved of 849kg per steel fixer per day.

There was a more significant difference, however, of 133kg between the questionnaire mean output of 982kg/steel fixer/day and the actual achieved output of 849kg/steel fixer/day.

- Contrastingly, Project B demonstrated a large increase in output of 4%, or 34kg/steel fixer/day. This was caused by a reduction in the planned duration of 5 days
- Of the six projects interrogated, only one, Project C, had the reinforcement installation completed in the planned duration.

- Project D demonstrated the largest reduction in duration, with the reinforcement installation completed 6 days earlier than planned, with a slight increase in the planned output to 1043kg/steel fixer/day.

A Pearson's Chi Square Test was performed on the relationship between the questionnaire results and the schedule analysis and a very high probability of dependence, 99.99%, between the planned values for reinforcement output and the questionnaire results was found, as shown in Table 7-5 below. The results indicate that the perceived level of reinforcement is accurately estimated by those who measure the output and those involved in the project planning stage.

Table 7-5. Chi Square Tests for Reinforcement Output

Chi Square Test Results	
Questionnaire and Predicted Values for Formwork Output	
P value =	5.30E-222% (sig >95%)
α =	0.05
Ho FALSE as P value < α, therefore dependency established	
Probability of H1=	**99.99%**
Questionnaire and Achieved Values for Formwork Output	
P value =	0.0000% (sig >95%)
α =	0.05
Ho FALSE as P value < α, therefore dependency established	
Probability of H1=	**100%**

The relationship between the reinforcement outputs achieved in practice and estimated by questionnaire participants was also subjected to a Pearson's Chi Square Test, refer to Table 7-5 above. Similar to the planned reinforcement outputs, the achieved outputs exhibited a very high probability of association of 100%. This result is an indication that those measuring progress have a very good concept of the actual outputs achieved in practice. Therefore, the results of the questionnaire and the schedules analysis are considered valid data to populate the planning knowledge database. Table 7-6 below illustrates the analysis of the reinforcement output planned and achieved for the six projects reviewed.

Table 7-6. Planned and actual steel fixer outputs

	Description	Schedule Reference					
		A	B	C	D	E	F
Planned	Quantity of Reinforcement (tonnes)	1446	448	212	1194	560	1525
	Quantity of Steel fixers	7	4	4	5	5	18
	Planned Duration of Reinforcement (Days)	175	130	98	235	120	84
	Planned Output (tonnes/steel fixer/day)	1.180	0.862	0.541	1.016	0.933	1.009
Actual	Actual Duration of Reinforcement (Days)	184	125	98	229	118	85
	Actual Output (tonnes/steel fixer/day)	1.123	0.896	0.541	1.043	0.949	0.997
Differences	Difference in Duration (days)	9	-5	0	-6	-2	1
		5.14%	-3.85%	0.00%	-2.55%	-1.67%	1.19%
	Difference in Output (tonnes/steel fixer/day)	0.058	-0.034	0.000	0.027	-0.016	0.012
		-4.89%	4.00%	0.00%	2.62%	1.69%	-1.18%
Note: Negative values indicate a decrease in output or quantity.							

Slab Cycle Time

As discussed in Chapter 1, the slab cycle time is the duration to complete one concrete slab, including the construction of vertical members (walls and columns), and the installation of formwork, reinforcement and concrete. For the six projects investigated, there was a variation in the average slab cycle time from the planned duration of 9 days to the actual duration of 8 days. This is at variance with the results of the questionnaire which indicate the average slab cycle time is 11 days, whilst the most common cycle time was found to be 10 days. The results in Table 7-7 below also illustrate that for the majority of projects (67%), there is no variation in the slab cycle time, and where variation is detected, it is small, at between 1 and 3 days' difference on average.

Table 7-7. Planned and Actual Slab cycle times.

	Schedule Reference						Mode
	A	B	C	D	E	F	
Planned Average Slab Cycle Time (days)	12	10	10	6	7	8	10
Actual Average Slab Cycle Time (days)	9	10	10	6	7	7	10
Difference in Slab Cycle Time	-3	0	0	0	0	-1	--
	-25%	0%	0%	0%	0%	-13%	-6.25%

The slab cycle times as estimated in the questionnaire by those whom measure progress were compared to the actual and the planned cycle times determined form the schedule review using a Pearson's Chi Square Test. It was found that there is a very high probability, at 99.71%, that a statistically significant dependency exists between the variables. Therefore, in common with the output rates for formwork and reinforcement derived from the questionnaire and schedule analysis, the slab cycle times are suitable for inclusion in the creation of baseline data values in the planning knowledge database.

7.3.3 Task Influence on Progress

Overall project progress is heavily influenced by the timely construction of the concrete frame, as the frame is typically on the project critical path, providing the structure for the remainder of the works. From the six schedules reviewed, all contained multiple contractual key milestone dates, which are overall project critical path dates on the project schedule. These critical path dates illustrate when a particular area, or specific floor level as is frequently the case of multi-storey concrete frames, is required to be completed and possession given to the client, permitting the commencement of follow-on trades and operations. Consequently, any delay to the key handover dates by the concrete frame contractor will have a critical impact on the overall project schedule.

Accurate knowledge of the schedule performance in terms of planned and actual tasks, in particular those on the critical path of the project will enable more accurate planning decisions to be made in the future. The creation of a knowledge base will enable the collection of performance data, in particular critical path performance data, and make this available for reference.

A review of the six concrete frame schedules with regard to schedule durations and key date requirements is illustrated below in Table 7-8, highlighting that the task durations for the formwork and reinforcement are significantly longer than the duration to cast concrete. Therefore, it follows that the two tasks of formwork and reinforcement installation are by far more critical to the construction of the concrete frame as they account, in isolation (although they do overlap), for 53% and 41% of the duration respectively, compared to 17% for concrete. This supports the findings of the literature review in Chapter 3, where formwork and reinforcement were found to be the critical elements of the work breakdown schedule.

Table 7-8. Schedule durations for formwork, reinforcement and concrete

	Schedule Reference						Mean Value
	A	B	C	D	E	F	
Overall Tender Duration (days)	432	237	179	390	345	441	
Actual Construction Duration (days)	520	255	200	405	289	599	378
Actual Duration of Formwork (days, and % of overall duration)	203	148	123	288	194	130	181
	39%	58%	62%	71%	67%	22%	53%
Actual Duration of Reinforcement (days, and % of overall duration)	184	125	98	229	118	85	140
	35%	49%	49%	57%	41%	14%	41%
Actual Duration of Concrete (days, and % of overall duration)	90	48	33	68	49	99	65
	17%	19%	17%	17%	17%	17%	17%
Quantity of Key Date Handovers influenced by Formwork, Reinforcement and Concrete	8	2	2	4	5	5	4

In projects where the concreting of floor slabs occurs on the critical path of the schedule, monitoring this single event (placing concrete) is of limited benefit as the singular process to assessing progress. Although monitoring concrete installation does infer that the preceding tasks are completed, it follows from above that it is imperative for formwork and reinforcement installation tasks between each concrete pour to be monitored for progress and not simply completion.

The actual task duration data also indicates there is a requirement for more accurate planning, in particular around the planning of form work and reinforcement installation. For instance, Project A (Table 7-3) was found to have delays of 18% of the formwork installation period, and Project D (Table 7-6) was found to have delays for 16% of the reinforcement installation period.

7.3.4 Accuracy of Measurement

The accuracy of the measured progress in the six schedules was established through a review of the progress recorded and the identification of any inconsistencies or irregularities. A principal indicator of inaccuracy in measurement is a sudden unexplained change in progress recorded for a particular task, where the output rates demonstrate a marked increase or decrease in production for no apparent reason.

Such an occurrence was identified in one of the schedules analysed, Schedule E, which showed an unexplained reduction in progress in one reporting period for the formwork. The following reporting period showed a large increase in production for that particular task without a reason given in the project report or in the schedule notes. This is an indication that, for those two periods, progress was not measured correctly initially, and then corrected the following progress period. However, the remaining five schedules were largely consistent and any sudden changes in output or progress were explained by notes in the project documentation. Therefore, based on the data available, the progress measurement is considered accurate as there is nothing to indicate to the contrary.

7.4 Chapter Summary

This chapter has reviewed six sample construction schedules and established baseline data from industry for the construction of RC frames, which may be used to update a database of productivity as identified in the conceptual framework in Chapter 4. With regard to baseline values, it has been found that the carpenter output experienced in delivery on site, at 8.82m^2 of formwork per carpenter per day, is 8.8% less than what was predicted at tender stage. However, the results from the questionnaire exhibit a probability of 99.964% that they are related to the value derived from schedule analysis. Similarly, the mean steel fixer output rate of 849kg of reinforcement per steel fixer per day was established as the mean output for project delivery through an examination of the group of six schedules. This output rate exhibits a reduction of 74kg from the planned output, and shows a 99.999% probability of association with the questionnaire results. In addition, the slab cycle time established from the schedules analysed also aligns closely with the questionnaire results, with a probability of 99.711%. Moreover, the schedules were found by inspection to be accurate, with consistent progress data entered in all but one instance. As a consequence of the foregoing, the data obtained from the delivery of six projects, in combination with the questionnaire responses, are accurate and suitable for use in the formation of baseline data for a planning knowledge database. Finally, this chapter has identified that there is a requirement to monitor the formwork erection and reinforcement installation tasks to overcome the creation of inaccurate schedules.

The following chapter explores the seven interviews carried out with operational staff from the RC frame sector, including planners, project managers, contract managers and directors.

8 Interviews

8.0 Introduction

The purpose of this chapter is to present the findings of the seven interviews carried out on practitioners from within the RC frame industry. The interviews were structured and semi-formal, and were conducted after the initial questionnaire survey analysis with the primary function of confirming the results of the questionnaire, in particular how progress is measured and the data employed for progress monitoring. This chapter includes a review of practitioners' opinions regarding the frequency and effectiveness of measurement, as well as what is measured and how it is measured. Furthermore, an examination and comparison of the questionnaire and interview output rates and slab cycle times is carried out, followed by a review of the accuracy of the measurement process. The results of the interviews are presented below in four sections, as follows:

1. Analysis of Response
2. How Progress is Measured
3. Data Requirements for Progress Monitoring
4. Decision Making Informed by Knowledge

These four sections relate to the collection of performance data from the available reference classes and will be analysed below.

8.1 Analysis of Response

There were seven interviews carried out, selected from colleagues, former colleagues and recommended candidates. There was a high success rate in securing interviews, with seven candidates selected and all agreeing to be interviewed. Five were internal candidates and two were external to the researcher's organization, with the external candidates viewed as essential to achieve balance, rather than the findings being skewed by the operational processes of one organisation. The interviews were conducted over the course of June, July and August of 2019 and consisted of four internal and three external interviewees. Three of the interviews were conducted face-to-face with the remaining four undertaken as telephone interviews, necessary as the interviewees found it difficult to accommodate a face-to-face meeting due to their workload.

8.2 How Progress is Measured

This section is a review of the interviewee's comments regarding how frequently they believe progress measurement should be undertaken, what elements of the project should be measured, how to measure progress and finally, their perception of how effective they perceive the measurement process to be.

8.2.1 Frequency of Measurement

In contrast with the questionnaire responses, one interviewee stated that monitoring a project weekly would often not be required as there would be insufficient progress to measure, stating that a fortnightly assessment is more appropriate. When pressed on this response, the interviewee confirmed that measuring incremental progress is not always the most appropriate method, that the frequency of progress measurement is dependent on the task in hand and the quantity of work allocated to that task. This results in a variety of measurement frequency – daily, weekly, fortnightly and monthly – which was explained by one interviewee, an Operations Director. He believes that the progress should be measured at different frequencies by different people, stating:

> 'I believe that progress should be measured daily by the site team, based on weekly plans. Weekly by the PM [Project Manager] and fortnightly [or] monthly by the Contracts Manager.'

In common with the results from the questionnaire responses and the schedule analysis, most of those interviewed stated that they measure progress weekly, although one interviewee, a Project Manager, stated that 'every day we track progress' and that it is reported weekly. One planner corroborated this position, stating that he maintained 'records of site progress daily' which then informed the weekly progress reports. This supports the findings of the questionnaire and will be used in the creation of the data collection tool, justifying user prompts to provide weekly progress data.

8.2.2 What to Measure

For the interviewees, formwork installation was most frequently identified as the preferred task used to measure progress. Three interviewees requested clarification and felt that the question could only be fully answered if a specific example was given as the variables are too numerous. Nonetheless, their views broadly concurred with the other interviewees, opining that formwork is the best measure of progress, although reinforcement and concrete tasks were also considered important.

Those more closely monitoring a project, in particular project managers, are more interested in measuring the progress at individual task level, including the disciplines of formwork erection and steel fixing in particular. These two tasks are seen by project managers as the primary schedule drivers for suspended slab construction. In contrast to this view, one interviewee stated that the optimum means of measurement was to evaluate the progress of the vertical elements, as 'the building can't progress without them'. The interviewee was very explicit about using vertical members as a barometer of progress, stating that 'you will get the best measurement [of progress] from this single source'. Despite this strongly-held opinion, this view was not shared by others.

All other interviewees recognised that there is a benefit in understanding and monitoring progress in areas other than concrete pours, in particular formwork and reinforcement as the other tasks, including vertical members and concrete pours 'fall into place after these'. The interviewees were in agreement that the reinforcement and formwork were a crucial part of the progress monitoring process, confirming the findings of the literature review, the questionnaire survey and the schedule analysis.

8.2.3 How to Measure

The main method of physically measuring the works with a view to gathering progress data is to use a measuring tape or optical engineering instruments, such as a total station. However, three of the interviewees indicated that this is not usually normal practice, only being undertaken when assessing valuations for work completed by subcontractors. In this case, the measurements are undertaken by the Quantity Surveyor on site, whom would occasionally engage the Site Engineer to assist in measuring large areas of formwork, for example, using a total station or similar equipment.

When a measurement of the work is performed in order to complete a progress assessment, it is normally undertaken 'visually', according to six out of seven of the interviewees, with the assessor selecting physical features such as columns to establish the location of known grid lines. When the position of the gridlines is identified, they provide a basis for measurement, with the percentage of formwork occupying each bay or section between gridlines determined using a combination of observation and measurement. This method supports the findings of the questionnaire, where 38% of Group A respondents stated that they assess progress through a combination of measurement and observation, whilst the vast majority (92%) of Group B respondents stated that they believed this is the method that should be used.

8.2.4 Effectiveness

The interviewees' opinion was largely positive when the effectiveness of their progress assessment methods was discussed, with five from seven people stating they believe their methods are effective, using encouraging terms such as 'reasonable', 'good' and 'very effective'. Two interviewees were not so enthusiastic, with one indicating that the measuring process 'could be improved for sure' and another clearly stating that the methods 'are not always effective'. The interviewee then described a scenario where a slab has a construction duration less than the progress measurement frequency resulting in no record of the duration of the component tasks being made. Recalling such an incident on a particular project, they noted the following:

> 'the start date and the completion date were captured, but not the duration of reinforcement [installation] or the duration of the formwork [erection].'

This potential problem was not evident from the questionnaire responses or the literature review and prior to the interview was not recognised as a threat to data collection. Nevertheless, this possible issue of hidden data will be addressed by the data collection tool requesting weekly updates on the output rates rather than simply task commencement and completion dates, as discussed in Section 9.2.

8.3 Data Requirements for Progress Monitoring

This section assesses the interviewee responses in relation to the data required to monitor progress, with a view to assessing divergence with the questionnaire survey responses. In particular, questions were posed to the seven interviewees regarding the outputs they would expect to achieve on site for carpenters erecting formwork, steel fixers installing reinforcement and typical slab cycle times.

8.3.1 Formwork Output

Several of the interviewees were cautious about generalising, with one stating that it 'depends on so much criteria', such as slab geometry, the height of the formwork and quality of labour. On the assumption that slab soffits are flat and the formwork is standard single storey height, the formwork output values provided by the interviewees gave a mean value of 11.9m^2 of formwork erected per carpenter per day. This closely corroborates with the mean output amount from the questionnaire responses of 11.8m^2/carpenter/day. Notwithstanding this similarity, both output values are greater than the schedule analyses values, where the mean values were found to be 8.901m^2/carpenter/day (actual) and 9.994m^2/carpenter per day (planned).

An important finding of the interviews was identified when four of the seven participants stated the output or production rate varies depending on the type of formwork system used. When proprietary panelised formwork systems are utilised, such as SkyDeck, DokaDek, MevaDec or Titan HV, the outputs were described as being significantly higher than the traditional prop-and-beam methods (as outlined in Chapter 2) with the four interviewees stating an average of 80m^2/day/carpenter. This information is useful as it highlights a requirement to include traditional and lightweight panel formwork options, which was not considered prior to the interviews. Provision was subsequently made in both the database and the task duration prediction algorithm to accommodate additional formwork systems, acknowledging the differing output rates.

8.3.2 Reinforcement Output

The interviewees indicated the average quantity as 1021kg of reinforcement fixed per steel fixer per day, only 4% different to the questionnaire data of 982kg/steel fixer/day, although the range of values given to the questionnaire survey was higher, between 500kg and 1500kg/steel fixer/day. When compared to the schedules analysed in Chapter 7, the value of 1021kg/day is marginally greater than the planned amount of 1019kg/steel fixer/day and 130kg larger than the actual output of 891kg/day. The interviewees also stated that critical variations may be experienced in the amount of reinforcement installed depending on the complexity of the scheduled reinforcement and the experience of the reinforcement detailer.

This view was elaborated by one interviewee who referred directly to the quality of the reinforcement detailing, indicating that it has a significant influence on the speed of fixing, notably when the reinforcement detailing function is outsourced to the Far East. In this condition, the detailing is not usually optimised for the UK market, where the labour is the expensive variable, rather than material, with the interviewee stating:

> ‘there are too many bar marks in the schedules. They need to have less [variation in bars on each schedule], even if this means the tonnage of steel is more. You save in the fixing time’.

8.3.3 Slab Cycle Time

The interviewees' mean estimate of 9.5 days to complete a slab cycle was shorter than the questionnaire respondents' mean duration of 11.5 days, although slightly greater than the actual (8 days) and the planned (9 days) slab cycle times derived from the schedule analysis. It is noted that there was some discrepancy evident between the interviewee's largest duration which, at 10 days, is 1.8 days less than the mean of the questionnaire responses on slab cycle time, indicating that the interviewees have a greater expectation of site performance than the average questionnaire participant.

One explanation for variations in expected slab cycle time were explained by one interviewee, whom expressed a view that the optimal slab duration was principally a function of the geometry of that slab, and occasionally smaller, more frequent concrete pours are sometimes preferable as '…it means less spikes in labour. Averaging out the labour is the best way to maintain momentum and de-risk the project'. Despite the divergence between the range of the interview and questionnaire slab cycle time results, both are very close to the planned and actual slab cycle times from the schedule analysis and are therefore concluded to be correct.

8.3.4 Factors Influencing Progress Measurement

The single most important factor for the assessment progress measurement, according to the questionnaire respondents, is the quantity of concrete floors constructed. This opinion has been clarified by the interviewees, where they all stated that identifying the progress of the concrete floors is a means to assess progress rapidly and without a great deal of accuracy. This approach was most commonly favoured by those at contracts manager and director level, as it provides a rapid overview of the project status against schedule.

There was also a common trait identified in the interviewee's responses when task influence was discussed. Whilst they all stated concrete slabs are important and influence the progress assessment, it was stressed that monitoring of the critical path is essential, irrespective of which element is involved. As one interviewee stated 'If concreting the slabs is one of the critical path items, then this is what should be monitored', with another stating that 'the critical path is always assessed'. One project manager indicated that he monitors critical path items, but will also monitor near-critical path tasks as 'other elements may become critical path [elements]'. It is therefore clear that critical path items are monitored, and whilst this often includes concrete slab pours, it is incumbent on the site management to assess all of the tasks on the critical path, including formwork, reinforcement and concrete.

8.3.5 Accuracy of Measurement

Interviewees believe that the most accurate way to assess progress is to physically measure the works, however some felt that this is not always possible due to time constraints and labour resource, with the interviewees in more senior positions indicating that they assess progress in a different method to site management. One interviewee stated that he would monitor a project closely, usually weekly or fortnightly, in the initial stages and then monthly thereafter when the project is established and running smoothly, so extremely accurate progress data is not required.

This was corroborated by those in senior positions who would typically visit a project rather than be project-based. They consider that a detailed accurate measurement was not necessary to enable them to have a broad understand of the progress, believing it is the responsibility of the site management to monitor progress closely. This is partly due, according to one director, because only a 'feel for how the project is progressing' was required. They stated that in instances where a project was falling behind schedule, it would be detected swiftly by their weekly assessment of the concrete pours and comparing this to the required or predicted schedule position. To achieve the most accurate results, it was found that observations and measurements should be performed daily, recording the amount of concrete placed, and the quantity of reinforcement installed.

8.4 Decision Making Informed by Knowledge

Interviewees were requested to identify the factors they believe have the greatest influence on the construction schedule and should be considered in greater depth when compiling a construction schedule. The most frequent response was the provision of cranes, which is unsurprising considering that the interviewees were all involved in the construction of high-rise RC frame structures. The complete list of schedule considerations highlighted by the seven interviewees is given in Table 8-1 below.

Table 8-1. Required Considerations to Compile Construction Schedule

Interviewee Responses		Interviewee Reference							Total
		IA	IB	IC	ID	IE	IF	IG	
Constraints	Provision of Cranes	1	1	1	1	1		1	**6**
	Interaction with Third Parties					2	1		**3**
	Weather		1			1		1	**3**
	Logistics		1	1				1	**3**
	Unforeseen ground conditions or incomplete soil investigation						1	1	**2**
	Incomplete construction information						1	1	**2**
	Safety		1						**1**
	Delays by preceding contractors	1							**1**
Methods	Overly-complex formwork designs					1			**1**
	Correct choice of plant				1				**1**
	Method				1				**1**
Production	Workforce competence and productivity						1	1	**2**
	Labour levels				1				**1**
Work	Incorporating precast concrete without any benefit					1			**1**
	Quality		1						**1**

With reference to the conceptual framework identified in Section 4.5, it may be seen that factors shown in Table 8-1 align with the production, constraints, methods and work components of the planning parameters identified in the Conceptual Framework and necessary to inform the planning algorithm, with regard to data collection and task duration prediction. This data shows that the provision of cranes for vertical transportation is an important constraint on construction schedules, however in a shortcoming of the data collection, it was not considered as a significant factor, something that is recommended for further research in Chapter 10 below.

8.5 Summary

It was found that the opinions of the interviewees largely supported the results of the questionnaire, including the preference to assess progress through a weekly review of formwork, reinforcement and concrete. There was confidence expressed by the interviewees that their method of assessment was accurate, although the point was made by senior management that a high level of accuracy is more important to site management.

Interviewees also expressed reasonable confidence in the effectiveness of the assessment methods used. Output rates and slab cycle times were found to be similar to the questionnaire results, although during four of the interviews many discussed the use of panellised formwork systems and how consequent increased productivity. This has highlighted a process which was not recognised in the questionnaire yet has a very large influence on output rates. This information has subsequently been used to justify identifying panelised systems as a formwork sub-category for inclusion in the database.

9 Development and Validation of a Planning Tool

9.0 Introduction

This chapter presents the novel planning tool, named Calchas after the Greek mythological seer, which uses a database of historic data to improve the accuracy of construction schedules. Developed in response to the inaccuracy of construction schedules, Calchas statistically analyses ongoing productivity and provides a prediction on the duration of proposed schedule tasks, specifically durations to erect formwork, to install reinforcement and to complete one full slab cycle in RC flat slabs.

The research question first identified in Chapter 1 was designed to provide a response to the problem identified in industry, that is, the inaccuracy of construction schedules. Chapter 6 has illustrated the primary data gathered through questionnaire surveys with regard to the research question, identifying how progress is measured, the type of data used to measure progress and how this data can inform decision making. An interrogation of six schedules in Chapter 7 then assessed the planned and actual outputs, identified the differences and then compared the results to the questionnaire data. It was found that there is close alignment between the planned and actual schedule data, and the data gathered from the questionnaires.

This chapter will now review the development of Calchas and the algorithms composed for performance data collection and task duration prediction. This is followed by validation of the process, where a demonstration of how the results of the gathered performance data, as discussed in Chapters 6, 7 and 8, were collated and utilised to inform the creation of the planning knowledge database. The trials performed on the tool are also discussed, comprising of the entry of test data, and the six schedules analysed in Chapter 7, assessing the planned and actual outputs and task durations and comparing these with the predictions based on the algorithm-derived forecasts.

9.1 Development of Calchas

The conceptual framework presented in Section 4.5 has been enhanced through the development of two algorithms. The first, Planning Algorithm A, has been based on the findings of Chapter 6, where the questionnaire survey investigated how progress is measured, and what data are required to measure progress. The second algorithm, Planning Algorithm B, originated from the planning equations in Chapter 2, and which were further developed in Chapter 4, where calculations are performed on the data to predict task durations. Chapter 7 then provided reference class data from sample construction schedules to populate the database, permitting a baseline of productivity to be established. Furthermore, the interviews discussed in Chapter 8 provided additional data on the construction process in the conceptual framework, in terms of the production, constraints, methods and data components.

In comparison to the conceptual framework in Chapter 4, it can be seen in Figure 9-2 that the development of two algorithms have enabled the creation of a tool to record, store, retrieve and use data and information relating to productivity. This permits the user to predict schedule durations with enhanced accuracy as the prediction is based on a statistical analysis of historic performance. Progressing from the current position to the prospective condition, using Calchas, the construction schedule is produced with improved accuracy.

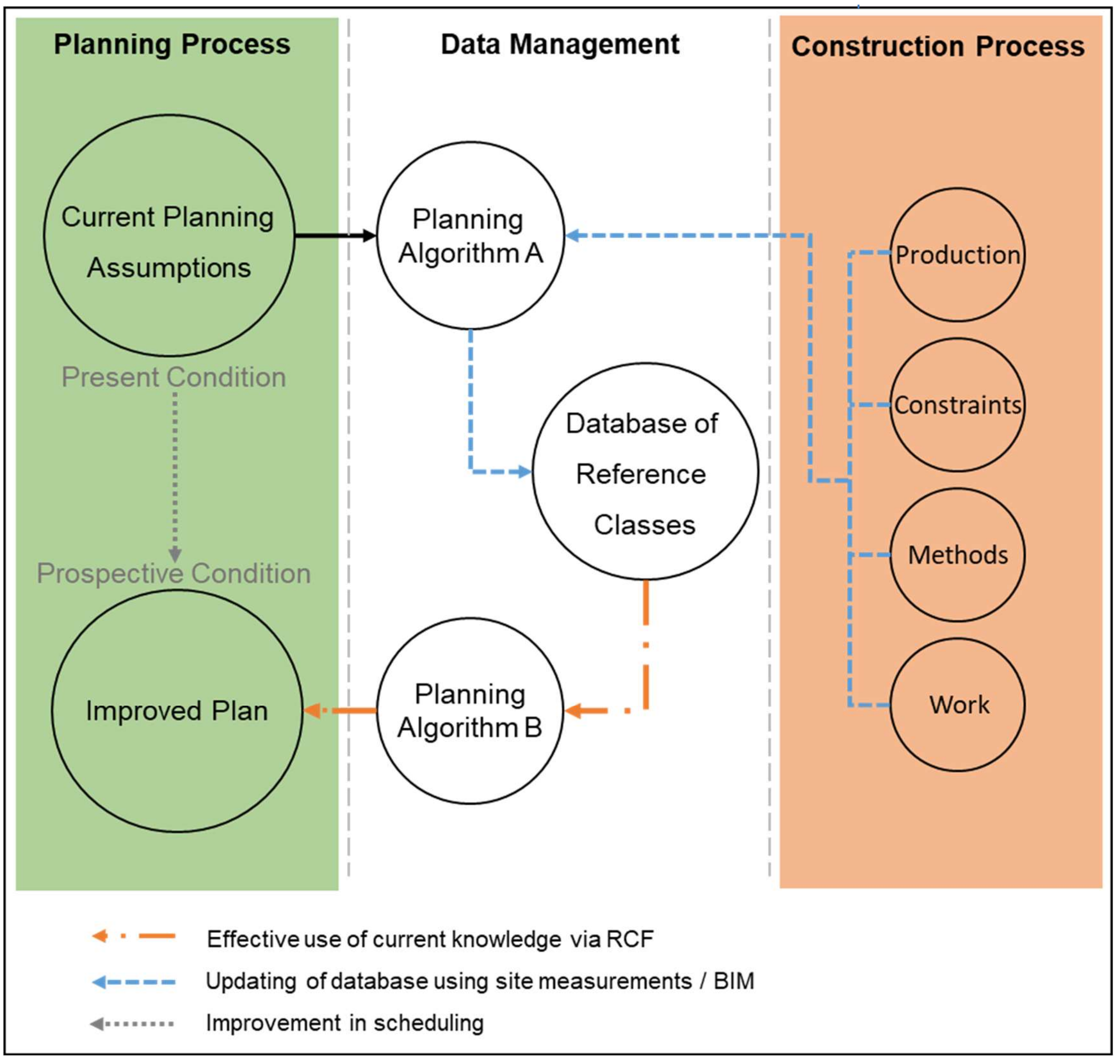


Figure 9-1. Calchas Prediction Tool

When using Calchas, the planner interacts with the database through the two algorithms as follows:

- Planning Algorithm A in Figure 9-1, is named the **Performance Data Collection Algorithm** (PDCA) and enables the user to record ongoing performance data from live projects, storing the data in the *planning knowledge database*. This database is a structured, searchable archive of reference durations and labour output rates which can be consulted when planning reinforced concrete frame projects.
- The second process, denoted by Planning Algorithm B in Figure 9-1 is the **Task Duration Prediction Algorithm** (TDPA), which is enabled through a simple data acquisition form completed in Excel where the user inputs details regarding anticipated labour levels and the geometrical properties of the reinforced concrete slab under review. The TDPA algorithm interrogates the performance data contained in the knowledge database, analyses them and proposes task durations based on the historical performance achieved for similar tasks. A correction factor is applied to the durations based on the accuracy of previous predictions with the task duration calculated automatically. This approach removes the requirement for estimation, heuristics and rules of thumb which are current features of planning, as identified in Chapter 2.

Figure 9-2 below shows the relationship between the collected data and the prediction of the task duration.

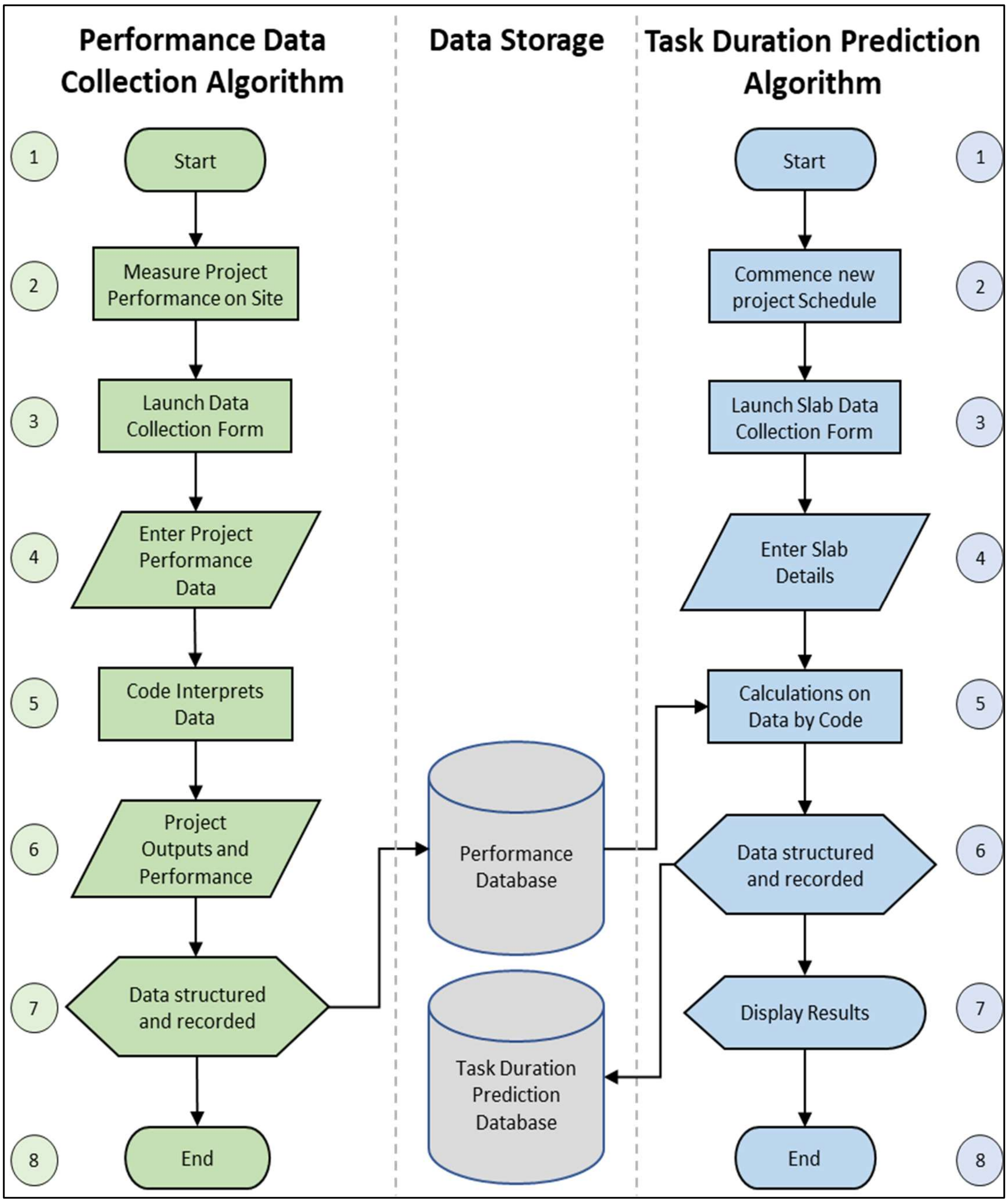


Figure 9-2. Novel Calchas algorithms

9.2 Development of the PDCA

This section presents the data collection algorithm illustrated in Figure 9-2 above, explaining how data is collected and stored, and describes the coding behind the collection and storage processes. The equations derived in Section 4 are also mapped to the data collection process, with their application and inclusion in the coding explained. The data collection algorithm is discharged through a script of code written in Visual Basic, created to manage the collection of weekly progress data entered by users. Visual Basic was chosen as it is a simple coding language designed to interface seamlessly with Excel and is easily understood, using plain

English words rather than symbols which are a feature of other languages, such as C#. For example, in Visual Basic, the operators 'or' and 'not' are used, whereas the C# equivalent symbols are '||' and '!'. The code complied for this research may be inspected in Appendix F. There are two components to the process: (i) the data collection form, and (ii) the data collection code, which are described in the following two sections.

9.2.1 Data Collection Form

This section relates to Steps 1 to 4 of the of the PDCA, see Figure 9-3 below, describing how the Data Collection Form (DCF) has been created in Visual Basic and its' use in collecting, sorting and storing production data, as identified in Figure 9-3.

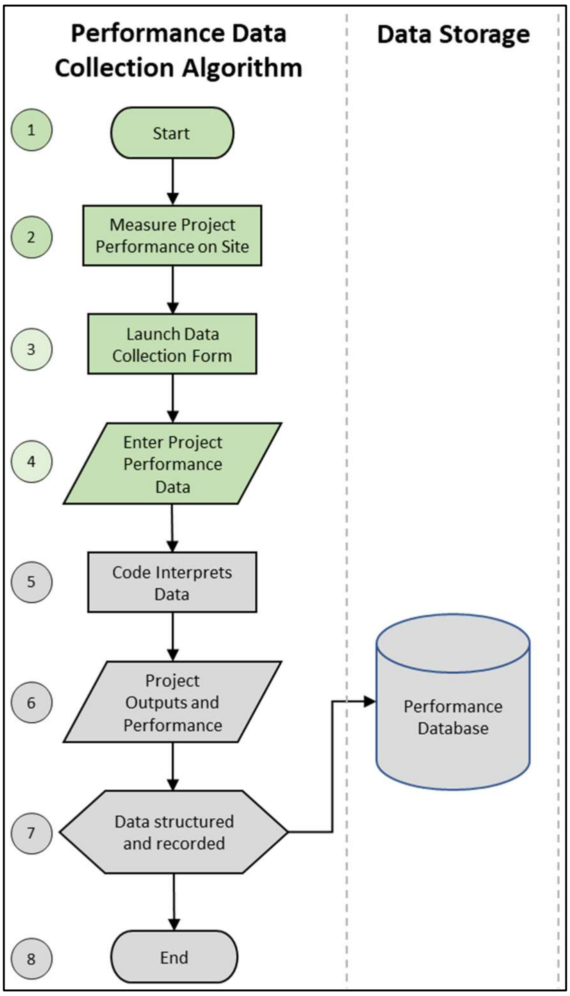


Figure 9-3. Steps 1 to 4 of the PDCA

9.2.2 Initialisation

Initialising the process (Step 1 in Figure 9-3) is followed by the collection of project performance on site, corresponding to Step 2 of the DCF algorithm. Here, relevant data is collected from the field in preparation for entry into the data form. To initialise the performance data collection form from the database spreadsheet (Step 3), the bright yellow ‘Click here to enter progress data’ button is selected (see). The macro-enabled button was created and linked using a macro named 'Output_Data_click’ to the data collection algorithm in Visual Basic.

When the button is clicked, a form is generated which requests a number of different inputs from the user to populate the database, including data relating to the formwork, reinforcement and slab cycle time. There is also a series of fields on the form which indicate to the user the project performance in comparison to the average performance of all projects in the database.

9.2.3 Data Entry

As the data entry form is generated in Visual Basic, it is straightforward to include controls which allow the user to input data in text fields, corresponding to Step 4 of the algorithm, and transfer this data to an excel spreadsheet. The form fields align with the database columns, with the first text boxes requesting details of the project and pour reference and the date of progress assessment, permitting the tracking of the performance of each project and facilitating further data analytics such as comparisons between specific projects or seasonal reductions in company-wide output, for example. The third user entry field requests users to indicate the type of formwork, which takes into account the views of the interviewees as outlined in Chapter 8, where it was stated that there is a large difference in carpenter output between traditional formwork systems and panelised proprietary systems.

Four of the seven interviewees reported a substantial increase in the carpenter output rate achieved when using the proprietary systems of approximately 80m^2/carpenter/day, compared with an output of approximately 11m^2/carpenter/day when the traditional method is employed. To take this variation into consideration, the user entry field for formwork type has been introduced to collect data generated on site regarding the output rates achieved for alternative systems. This will facilitate analysis in the future when sufficient data has been gathered to establish if the enhanced output rate claims are substantiated, based on user data. Figure 9-4 below shows the form prior to, and following data entry with the output rates calculated and displayed.

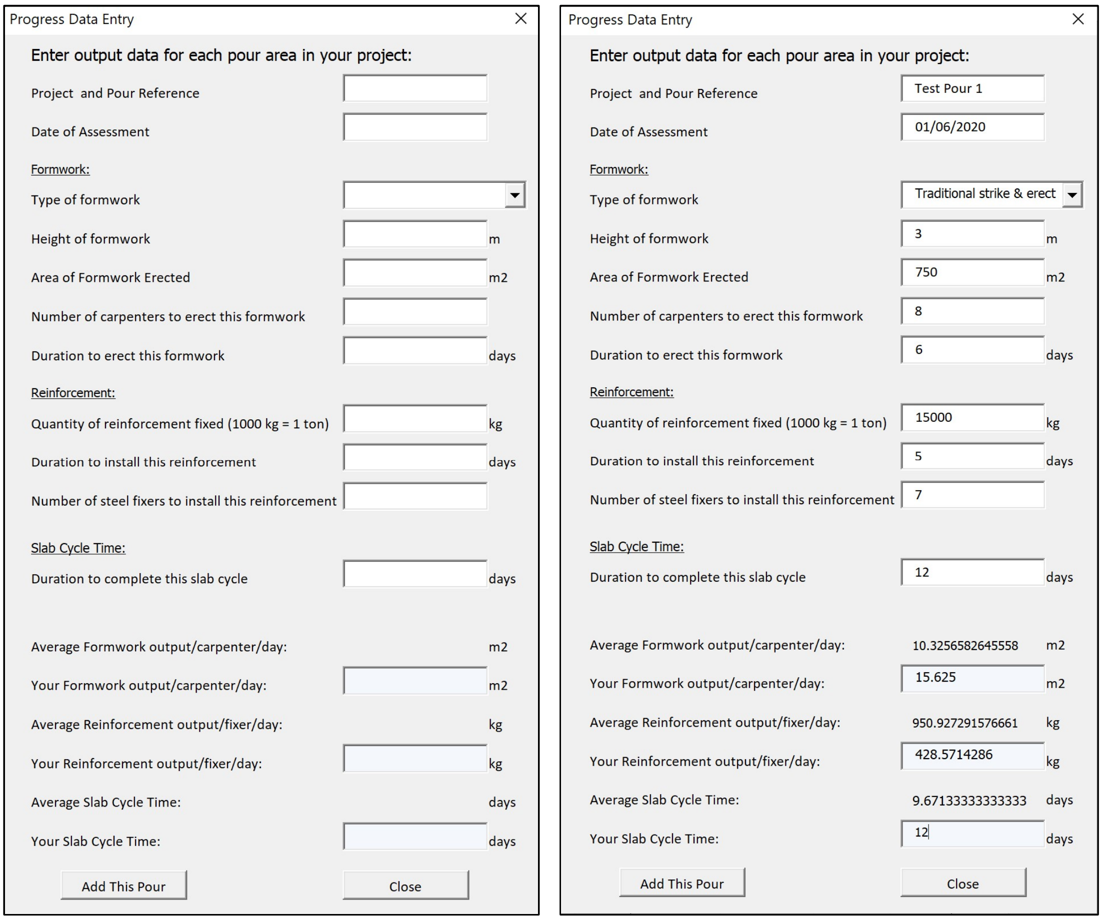


Figure 9-4. Progress Data Entry forms (left) blank and (right) completed

Similar to the rationale above regarding the type for formwork employed, a form field has been introduced to collect data relating to the formwork height, as highlighted in Chapter 2 and Section 9.2.6 below. The formwork height field was introduced to permit analysis of the effect of formwork height on productivity when sufficient data has been gathered. The analysis of the height and performance data will also allow the database owner to recognise if a number of separate height categories are required to alleviate skewness and manage the data. In addition to developing an accurate mean output, this approach also has the benefit of enhancing the accuracy of the formwork duration presented by the task duration prediction algorithm, as the calculations therein can be informed and modified by the soffit heights.

9.2.4 Form Completion

The remaining formwork fields require the user to input the area of formwork erected, the number of carpenters required and the duration to erect the formwork. Following this, the reinforcement data is requested, and includes the quantity of reinforcement installed, the duration to install it and the number of steel fixers required. Finally, the slab cycle time is requested, although this is not a required field as a full slab cycle may not be completed in the progress period. If the formwork or reinforcement fields are not completed in full, a warning message is presented to the user to re-enter the data correctly, such as shown in Figure 9-5 below.

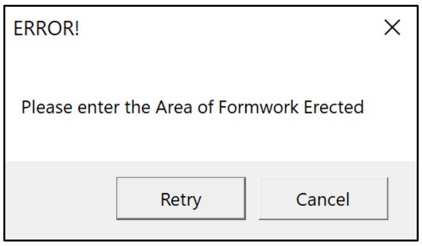


Figure 9-5. Error message to prompt the user to complete the data entry in full.

When the form is completed, the progress data is then uploaded to the database when the ‘Add this pour’ button is selected, using a set of code to distil the progress details into the appropriate database columns. The output is calculated within the algorithm for both carpenters and steel fixers, and this information, together with the achieved slab cycle time, is presented to the user. The average formwork, reinforcement and slab cycle time values are then displayed, allowing the user to compare their performance with that of all other projects.

9.2.5 Data Collection Code

This section outlines the algorithm for the data collection code compiled in VB to generate a form in Excel, with a view to gathering data relating to site progress and outputs. To enable communication between the user form and the database spreadsheet, there are several lines of code required. As previously described, clicking on the data entry button in the spreadsheet initialises the DCF via a macro called ‘Sub Add_Data_Click()’ which is associated with the button on its’ creation in the spreadsheet. In the Visual Basic interface, the form is constructed using a combination of standard command building blocks such as Label, Text Box, Combo Box, Command Button and Message Box. When assembled, the text boxes and combo boxes are where the user enters data, which are interpreted and the project outputs and performance are calculated, corresponding to Steps 5 and 6 of the PDCA, as shown in Figure 9-6.

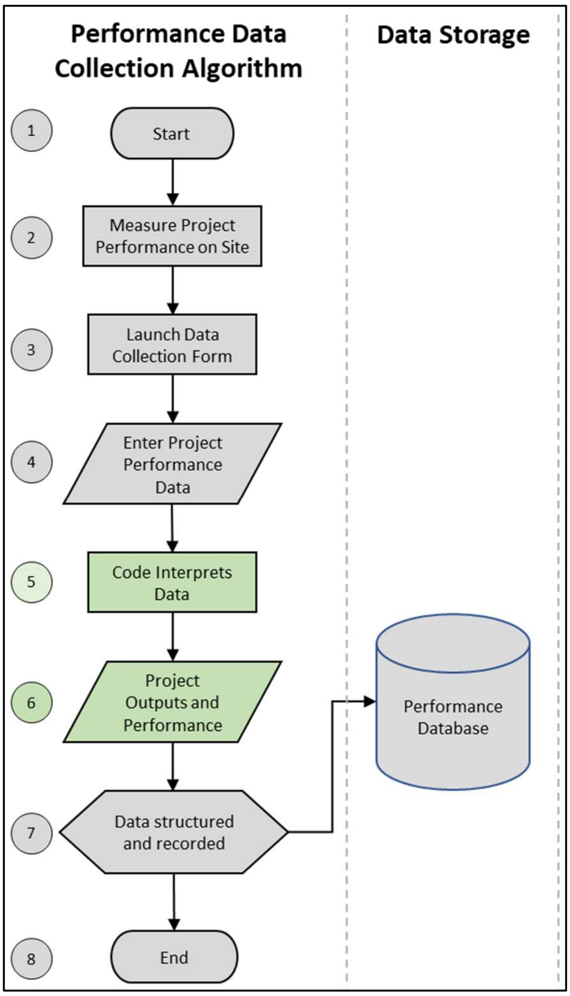


Figure 9-6. Steps 5 and 6 of the PDCA

It is crucial to maintain order and structure to the data, as this permits automated calculation execution, consistent formatting, and interaction with associated pivot tables such as the Data Summary tables described in Section 9.2.6. The next significant piece of code creates an association between the text box fields in the DCF completed by the user, and the columns in the database where VB code controls the transfer of data to the correct location in the database. To maintain process consistency and eliminate error or user manipulation of the database values, the calculation of the output rate is performed by the algorithm prior to entering the value in excel. *Equation 2-1* and *Equation 2-2* define output rates achieved as the quantity of work done divided by effort. These two equations may be expressed in a generalised form as follows:

$$Output\ Rate = \frac{Q}{(L * D)}$$ *Equation 9-1*

Where:

Q is the quantity of work; L is the amount of labour and D is the duration to carry out the work. The code to perform this calculation for the formwork and reinforcement, and enter the result in the appropriate cells in the database, corresponds to Step 6 of the PDCA.

To ensure that the user enters data in each form field, apart from the slab cycle time as stated in Section 9.2.1 above, code has been included to produce message boxes similar to that shown in Figure 9-5 above. The code is triggered when the user attempts to partially complete the data entry form and send the data to the database by clicking on the ‘Add Data’ button. As the algorithm cannot perform the calculation to determine the output with partial data, the code prohibits the user from sending any data to the database without completing each field in the form.

When the user has completed the data entry, the form also displays the average slab cycle times and the outputs for formwork and reinforcement, with the user outputs and slab cycle times displayed for ease of comparison by the user. This allows the Project Manager or Planner to identify their performance and compare it to the mean performance values achieved on other projects. The script to show the average output and slab cycle time firstly reads the average values stored in the database, and then displays them in the Progress Data Entry form. The output rates and slab cycle time values achieved on the user’s project are also shown using the previously defined variables and displaying them in a text box.

When the user clicks on the ‘Close’ button to terminate the form, code has been included to delete the values entered in the text fields to ensure they are blank when the form is subsequently initialised, enhancing usability. If this step is not performed, the data will remain on the form when next opened and would burden the user with deleting the previous progress data in each field and then enter new details.

When the data collection form is closed, the database is populated with all of the user-inputted data, the calculated outputs, the slab cycle time and icons and text strings indicating the performance of the project, indicated by Step 7 in the PDCA, see Figure 9-7.

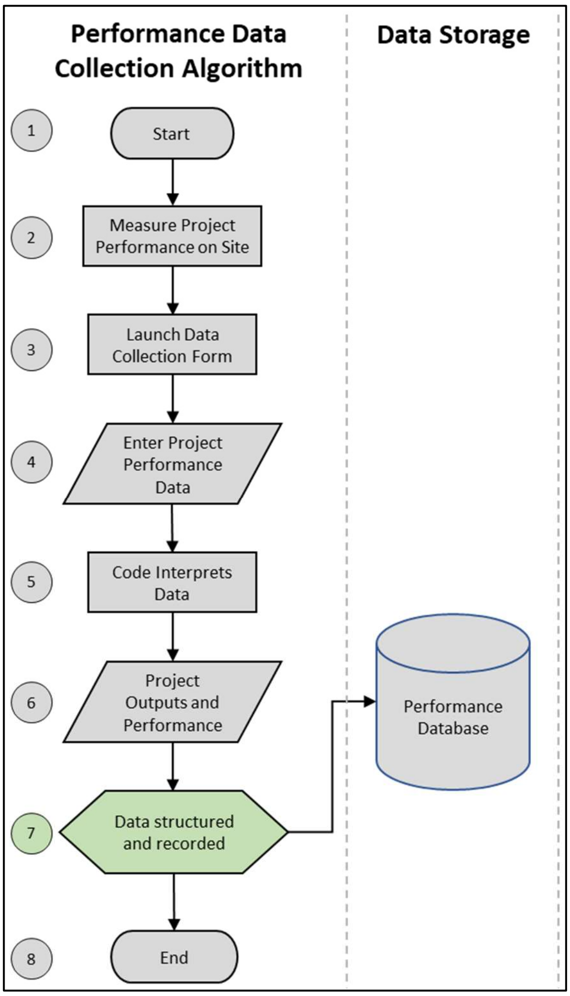


Figure 9-7. Step 7 of the PDCA

The ideal condition is to repeat this process for each project each week to generate a ‘data lake’ of performance data and knowledge relating to site productivity, providing information on which the user may base planning decisions. In addition to providing the user with a knowledge base for reference, it presents corporate management with a benchmarking tool to gauge individual project and company-wide performance, enabled through the use of pivot tables and Excel data analysis tools.

9.2.6 Performance Database

This section describes the database of production rates which is central to the two algorithms, linking the collection and use of the site production data, as shown in Figure 9-2. As illustrated by the database extract in below, the data is contained in two tables, the Data Summary table and the Site Performance Data table, with column headings coloured to highlight the data entered by the user through the data collection form (dark blue) and the information which has been calculated by the data collection algorithm code (green).

Database of RC Slab Production Rates

Site Performance Data

Click Here to Enter Progress Data

Data Summary Table

Actual (Achieved) Mean Values			Planned Mean Values			Mean Absolute Deviation of Actual Data			Mean Absolute Deviation of Planned Data			Modified Pearson's R (RA2)		
Mean of Actual Formwork Output	Mean of Actual Reinf. Output	Mean of Actual Slab Cycle Time	Mean of Planned Formwork Output	Mean of Planned Reinf. Output	Mean of Planned Slab Cycle Time	MAD of Actual Formwork Output	MAD of Actual Reinf. Output	MAD of Actual Slab Cycle Time	MAD of Planned Formwork Output	MAD of Planned Reinf. Output	MAD of Planned Slab Cycle Time	Reliability for Formwork Output	Reliability for Reinf. Output	Reliability for Slab Cycle Time
9.29	924.61	8.17	9.66	923.48	9.17	0.73	137.74	1.50	0.92	148.20	2.17	0.9934	1.000	1.000
m2	kg	days	m2	kg	days	m2	kg	days	m2	kg	days			

LEGEND

Column Headings: Data input by user; Calculated data

Perfromance Indicators:
- ● (green) Project is performing better than or equal to average
- ● (red) Project is perfroming below average. Action required

Site Performance Data Table

Updata data weekly using the yellow button above

Project Reference	Progress Assessment Date	Formwork Type	Height of Fomrwork (m)	Area of Formwork installed in period in m2	Duration to Install Formwork in days	No. of carpenters	Carpenter Output m2 /carp/day	Quantity of reinf. fixed in period in kg	Duration to install reinf. in days	No. of Fixers	Fixer Output kg/steel fixer/day	Slab Cycle Time	Formwork Output Commentary	Reinforcement Output Commentary	Slab Cycle Time Commentary	Planned Slab Cycle Time	Planned Formwork Output	Planned Reinf'mnt Output
Questionnarie Data	01/06/2020		0				● 11.83				● 982.36	● 11.51	Project is beating average formwork output	Project is beating average reinforcement output	Project is NOT ACHIEVING average slab cycle time. Consider taking action such as changing the labour quantity or methods of working			
Interview Data	01/05/2020		0				● 11.90				● 1021.00	● 9.50	Project is beating average formwork output	Project is beating average reinforcement	Project is NOT ACHIEVING average slab cycle time.			
Project A	08/01/2020	Traditional strike & erect	3.2	27550	203	14	● 9.69	1446	184	7	● 1122.67	● 9.00	Project is NOT ACHIEVING average formwork output. Consider taking action such as changing the labour quantity or methods of working	Project is beating average reinforcement output	Project is NOT ACHIEVING average slab cycle time. Consider taking action such as changing the labour quantity or methods	12	10.36	1180.41

Figure 9-8. Extract of Knowledge Database with baseline data entered

The first table is titled **Data Summary** and is located in the upper section of the spreadsheet, offering an instant, summarised view of the performance data contained in the database. The values are calculated automatically through the use of a pivot table in Excel, which has been modified to display the mean of the outputs and slab cycle times in the database, the MAD of Actual and Planned outputs and the correction factor values for formwork, reinforcement and SCT, as identified previously in Chapter 4. Figure 9-9 shows an extract of the Data Summary table.

Data Summary Table					
Actual (Achieved) Mean Values			Planned Mean Values		
Mean of Actual Formwork Output	Mean of Actual Reinf. Output	Mean of Actual Slab Cycle Time	Mean of Planned Formwork Output	Mean of Planned Reinf. Output	Mean of Planned Slab Cycle Time
9.29	924.61	8.17	9.66	923.48	8.83
m2	kg	days	m2	kg	days

Figure 9-9. Extract of Data Summary Table from the database spreadsheet

In addition to this information, a further benefit of using a pivot table in Excel is that it can be used to analyse the database contents in greater depth, such as filtering data by formwork type, for example, and allows other features such as pivot charts to be created if the user wishes to explore the data graphically. The main outputs of the Data Summary table are the MAD values and the modified Pearson's R as first identified in *Equation 4-5*. These values, an extract of which are shown in Figure 9-10, are subsequently used as reference data in the task duration prediction algorithm to augment the planner's estimation of output, proposing a corrected duration for the slab cycle time.

Mean Absolute Deviation of Actual Data			Mean Absolute Deviation of Planned Data			Modified Pearson's R (RA2)		
MAD of Actual Formwork Output	MAD of Actual Reinf. Output	MAD of Actual Slab Cycle Time	MAD of Planned Formwork Output	MAD of Planned Reinf. Output	MAD of Planned Slab Cycle Time	Reliability for Formwor k Output	Reliability for Reinf. Output	Reliability for Slab Cycle Time
0.73	137.74	1.50	0.92	148.20	2.17	0.9934	1.000	1.000
m2	kg	days	m2	kg	days			

Figure 9-10. Extract of Data Summary Table showing Modified Pearson's R

The main table in the database is titled **Site Performance Data** and contains a number of columns encompassing data and information on formwork, reinforcement and slab cycle times. Additional details, such as project reference, progress assessment date and labour levels are also included, as well as columns for the type and height of the formwork. The formwork columns include details of the area of formwork, the installation duration, the quantity of carpenters and finally the carpenter output, expressed in square metres of formwork installed per carpenter per day. A similar approach is used to organise the reinforcement data, where separate columns contain details of the quantity of reinforcement installed, the duration to install it, the quantity of steel fixers and reinforcement output, which is the achieved steel fixer output in kg of reinforcement fixed per steel fixer per day. The Site Performance Data table has been saved formally in Excel as a Table, permitting enhanced functionality, in particular the continuation of conditional formatting, formulae and pivot table analysis, and the expansion of the table automatically to include subsequent rows of data inserted by the data collection algorithm.

The Site Performance Data table is organised in a structure based on the current state-of-the-art methods of construction as identified in Chapter 2. That is, the columns of the database contain data collected from progress monitoring in either its raw state or which has been modified by calculation. In order to create trust in the information provided by the spreadsheet, and to permit transparency and control over the process, iterations of the planning calculations are displayed in the database to permit the user the opportunity to interrogate the data, retaining control and providing the ability to amend the results if required. Consequently, the user may accept or reject all or some of the calculations, maintaining complete control over the final schedule. The first two values in the database are project reference and progress assessment date, although additional user-defined fields may be introduced to include identifiers such as floor level, the name of the person entering the data and the date of entry, the name of the person whom assessed progress, and so forth, as required. The next column contains the height of the formwork, an important factor as the installation of formwork is influenced by the floor to ceiling height as outlined in Chapter 2; see Figure 9-11 below. Although this has not formed part of the questionnaire investigation, the rationale for including this column is explained in section 9.2.1 above. The output rate can therefore be modified to take account of an increase in duration and consequent reduction in carpenter output rate.

Project Reference	Progress Assessment Date	Formwork Type	Height of Fomrwork (m)	Area of Formwork installed in period in m	Duration to Install Formwork in days	No. of carpente	Carpenter Output m2 /carp/day
Questionnarie Data	01/06/2020		0				11.83
Interview Data	01/05/2020		0				11.90
Project A	08/01/2020	Traditional strike & erect	3.2	27550	203	14	9.69

Figure 9-11. Extract of database, showing columns relating to formwork.

9.2.7 Initiating the Database

A fundamental concept underpinning the database is that the set of data will increase over time, based on progress measurement data populated by project managers.

The findings from the questionnaire, interviews and the schedule analysis suggest that the optimal frequency for assessing and recording progress is at least weekly, as prompted by the data collection form. When all projects within an organisation feed into the database weekly, continuous improvement will be facilitated through increasing the statistical population and consequently enabling the mean performance data to continually increase in accuracy.

Initially, the database contains no entries, preventing the calculation of mean performance data to develop new schedule task durations. To overcome this problem, a baseline of data was created, comprising of the questionnaire responses and the schedule and interview analysis. It is recognised that the questionnaire data provided by respondents will more than likely suffer from optimism bias as it is unlikely to be actual project performance data, rather memories of what was achieved. However, it was decided to include the mean of the questionnaire survey data to provide a comparison of data. Table 9-1 below shows a summary of the output data established in previous chapters which was used to create the database baseline data. To create accuracy in the database, the 'planned' data from the schedule analysis was omitted in favour of the actual values achieved.

Table 9-1. Baseline data identified from research

Description	Mean Value
Questionnaire Data	
Carpenter Output (m2/carp/day)	11.829
Steel fixer Output (kg/steel fixer/day)	982.357
Slab cycle time	11.514
Schedule Analysis: Formwork	
Actual quantity of carpenters	11.50
Actual Duration of Formwork (days)	181
Actual Output (m2/carp/day)	8.822
Schedule Analysis: Reinforcement	
Actual Quantity of Reinforcement (kg)	883.50
Actual Quantity of Steel fixers	7.67
Actual Duration of Reinforcement (Days)	139.83
Actual Output (kg/steel fixer/day)	849
Schedule Analysis: Slab Cycle Time	
Actual Average Slab Cycle Time (days)	10
Interview Data	
Carpenter Output (m2/carp/day)	11.9
Steel fixer Output (kg/steel fixer/day)	1021
Slab cycle time	9.5

The baseline data in the database at this stage was available for use by the planning algorithm to recommend task durations for formwork and reinforcement installation. The Mean Absolute Deviations, or Correction Factors, shown for each element are used to adjust task durations when the database is consulted to predict durations and is essentially the output from the database; the input consists of project progress measurement data entered weekly using a data form and coding to distil the data into the database, performing calculations where required. The process of how the progress data is collected and entered into the database is explained in Section 9.2 below.

When the data in Table 9-1 was recorded in the database, calculations of mean values for the material quantities, outputs and slab cycle times were performed, as shown in the algorithm flowchart in . It was found that, based on these figures, the mean carpenter output was 10.85m^2/carpenter/day, the mean steel fixer output was 951kg/steel fixer/day, and the average slab cycle time was 9.7 days. In addition to displaying the mean performance, the spreadsheet also provides a comparison between the project outputs and slab cycle time achieved and the mean database values. Depending on the outcome of the comparison, cells in the database have been conditionally formatted to highlight the project performance, providing instant feedback to the user on how they compare to other projects, see Figure 9-12 below.

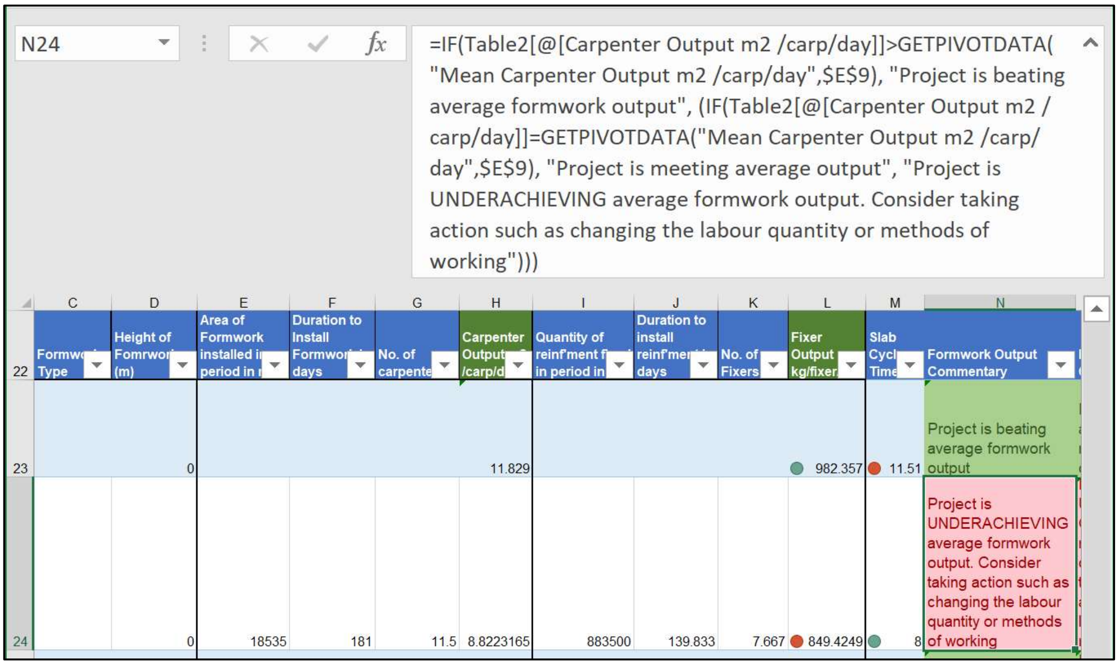


Figure 9-12. Database extract showing function for output commentary display

There are two strands to the conditional formatting and the first, a traffic light icon, is displayed in the cell containing the output value. A red icon indicates the performance below the mean and a green icon indicates the project is performing better than, or equal to, the mean. Secondly, commentary is displayed regarding the performance. In the case where the output is less than the mean, the comment also prompts the user to consider corrective action such as changing the labour quantity. With reference to the Excel function in Figure 9-12, formwork progress data is less than the baseline reference for formwork output, prompting the red traffic light icon and commentary to be displayed.

The following section describes the algorithm constructed to read the database and provide the user with valuable, fact-based information.

9.3 Development of the TDPA

The Task Duration Prediction Algorithm is the second algorithm shown in Figure 9-2 above and uses the collected data to predict task durations and is explained in detail in this section. As outlined in Chapter 2 above, the process of preparing a construction schedule involves the planner considering several variables whilst using experience and rules of thumb, to determine project task durations based on the geometric properties of the scheme. This was also confirmed in Section 6.2 above by the questionnaire participants, where the majority of those creating schedules use 'experience and intuition' (54%), with a considerable amount (41%) using 'rules-of-thumb' to estimate task durations. The use of the TDPA will reduce this reliance by planners and project managers on non-scientific means of schedule estimation. This will be accomplished through the use of the data stored in the knowledge database as reference to predict the length of time to complete a particular task. It was found in the literature review in Chapter 3, and confirmed by the questionnaire results in Section 6.5 and the schedule analysis in Section 7.3.3, that the most critical elements to the duration of a floor slab are the erection of the formwork and the installation of the steel reinforcement. The algorithm predicts the duration of formwork and reinforcement tasks for a reinforced concrete floor slab pour by performing automatically the calculations normally undertaken by a planner, as discussed in Chapters 2 and 3.

For ease of access, performing calculations and cross-referencing of the output data, the spreadsheet is located in the same Excel file as the Database of RC Production Rates, although located in a separate sheet. Similar to the PDCA, the TDPA is also written in Visual Basic for the same reasons as listed in Section 9.2 above, including ease of use and seamless interoperability with Excel.

The three components of the task duration prediction, the spreadsheet which contains the predicted task duration, the user interface form for data input, and the Visual Basic code underpinning the form, are now explained in further detail.

9.3.1 Task Duration Prediction Spreadsheet

The Task Duration Prediction Spreadsheet contains the predicted task durations for formwork and reinforcement, based on data input by the user and the Mean Absolute Deviation of the output values from the knowledge database. This approach is key in predicting the most accurate output, and consequently task duration, as it bases the outputs on the historic performance collected in the database, taking into consideration outlying data points. An extract of the spreadhseet is shown in below and it may be seen that it contains two tables, the first is a pivot table similar to that found on the Database of RC Slab Production Rates, permitting the data to be interrogated as outlined in Section 9.2.6 above.

The second table contains a number of columns of data and information displaying the data transferred from the user form, including the results of the calculations executed on the data by the code. Each data field is entered automatically in a separate column, the heading colour indicating whether the column contains raw form data or a value calculated by the algorithm. The table is stored as an Excel Table to permit deeper concrete pour analysis as required, such as sorting by project name or concrete slab size. The spreadsheet also conatins a button with the text 'Click Here to Enter Suspended Slab Details' which initialises the task duration prediction algorithm from the Slab Duration Data spreadsheet. The button was created and linked, through a macro executable file, to the algorithm, in a manner similar to the Data Collection form launch procedure. below shows an extract from the Task Duration Prediction spreadsheet, illustrating the button, the data summery table and the main database.

Task Duration Prediction

Enter Suspended Slab Data

Data Summary Table

Actual (Achieved) Mean Values			Planned Mean Values			Mean Absolute Deviation of Actual Data			Mean Absolute Deviation of Planned Data			Modified Pearson's R (RA2)		
Mean of Actual Formwork Output	Mean of Actual Reinf. Output	Mean of Actual Slab Cycle Time	Mean of Planned Formwork Output	Mean of Planned Reinf. Output	Mean of Planned Slab Cycle Time	MAD of Actual Formwork Output	MAD of Actual Reinf. Output	MAD of Actual Slab Cycle Time	MAD of Planned Formwork Output	MAD of Planned Reinf. Output	MAD of Planned Slab Cycle Time	Reliability for Formwork Output	Reliability for Reinf. Output	Reliability for Slab Cycle Time
9.29	924.61	8.17	9.66	923.48	9.17	0.73	137.74	1.50	0.92	148.20	2.17	0.9934	1.00	1.00
m2	kg	days	m2	kg	days	m2	kg	days	m2	kg	days			

Duration Prediction

Click on yellow button above to enter details of suspended slab.

Predicted durations for formwork and reinforcement (rebar) tasks will then be provided below.

NOTE: IF ALTERATIONS ARE REQUIRED, USE FORM TO RE-ENTER !

AMENDED CELL VALUES WILL NOT RE-CALCULATED AUTOMATICALLY

LEGEND

Column Headings: Data input by user / Calculated data / Task Duration Predictions

Project and Pour Reference	This Slab Level (mAOD)	Slab level below this slab (mAOD)	Slab Thickness (mm)	Soffit Level (mAOD)	Height of formwork (m)	Area of Formwork (m2)	Volume of Concrete (m3)	Density of Rebar (kg/m3)	Quantity of Rebar (t)	Formwork Output (m2/carp /day)	Formwork Output with Correction Factor Applied	No. of Carpenters	Corrected Duration to Install Formwork (days)	Corrected Formwork Duration Rounded Up (days)	Rebar Output (kg/fixer /day)	Rebar Output with Correction Factor Applied	No. of fixers	Corrected Duration to install rebar (d)	Corrected Rebar Duration Rounded Up (days)	Slab Cycle Time (days)	Slab Cycle Time with Correction Factor Applied (days)	Corrected Slab Cycle Time Rounded Up (days)
Test 1	**104**	**100**	**305**	103.70	3.69	**27550**	8402.75	**172**	1445.27	**10.36**	**10.30**	14	191.12	**192**	**1.18**	1.18	7	174.97	175	12	12	12
Test 2	**8**	**4.7**	**275**	7.73	3.03	**500**	137.50	**155**	21.31	**12**	**11.93**	5	8.39	**9**	**0.95**	0.95	5	4.49	5	10	10	10
Test 3	**44**	**40.5**	**300**	43.70	3.20	**450**	135.00	**175**	23.63	**11**	**10.93**	3	13.72	**14**	**1**	1	5	4.73	5	9	9	9

Figure 9-13. Extract of Task Duration Prediction Spreadsheet

9.3.2 Data Input Form

The Data Input Form is a form developed in VB as part of the TDPA. Referring to Figure 9-2 above, the first step in the TDPA is to start the process, followed by Step 2, which is to commence compilation of a new construction schedule. During this step the geometric properties of each slab pour will be established by the user, including the pour size, storey height and the reinforcement content, see Figure 9-14.

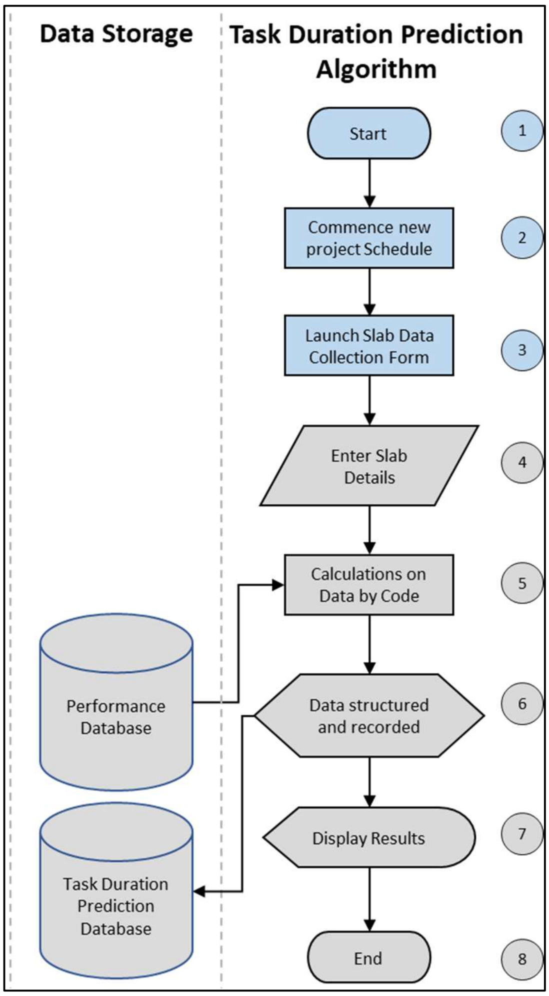


Figure 9-14. Steps 1, 2 and 3 of the TDPA

Step 3 relates to the user launching the slab data collection form triggered by clicking on a spreadsheet button. The associated code created in VB then presents a form containing a series of text boxes which request details relating to the concrete slab under review. The geometric and structural properties of the slab are entered into the form fields, including the slab thickness, the slab area and the density of reinforcement. As detailed in Chapter 2, this data is extracted from the tender documentation typically provided by the Client, including drawings and specifications. In addition, data relating to the resources the planner wishes to utilise are also entered, including the output rates and quantity of specific trades to be utilised. Figure 9-15 below shows the user interface form with blank data fields available for data entry. There are ten fields for the user to enter text in two sections, Slab Properties and Resources, and are explaied below.

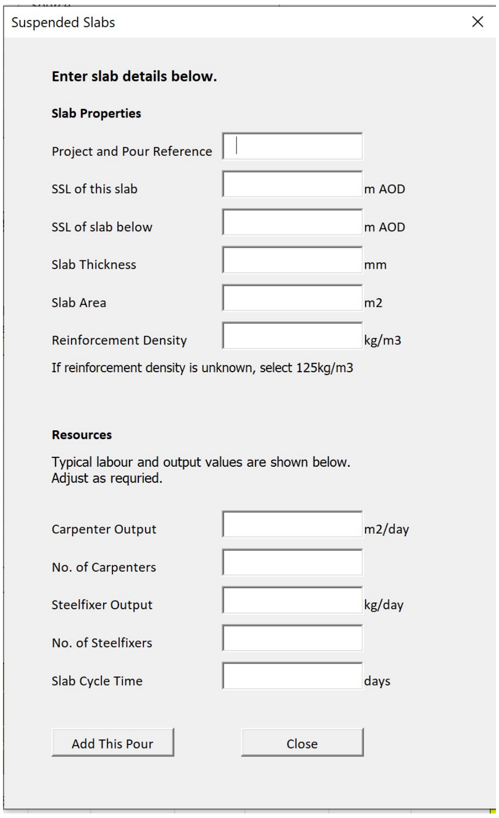


Figure 9-15. User Interface to enter Slab Data

The **Slab Properties** section refers to the geometric properties of the slab under review, the first being the Pour Reference, which prompts the user to identify the project and the pour for ease of identification of the data set later. Pour references would normally include the floor level and the sequential number of the pour, however there is no required format or text restriction in this form field. The second and third data entry fields relate to the structural slab level, or SSL, of the slab under review and of the slab underneath it, in metres above Ordinance Datum. This is necessary to allow a later calculation to be performed to determine the height of the form work required. As outlined previously in the PDCA discussion in Section 9.1 above, it is likely that there will be additional time required to erect higher formwork. In the absence of data in the knowledge database to predict the additional durations required for higher formwork, the planner will need to make adjustments to the duration. The state-of-the-art review of the planning process oulined in Section 3.2 found that there are rule-of-thumb guidelines for estimating the additional duration related to the formwork height, which are provided on the data prediction spreadsheet and may be used to modify the duration.

The fourth field allows the user to enter the slab thickness, which is the depth of the concrete in millimeters, with the fifth and sixth data entry fields prompting the user to enter the slab area and the reinforcement density respectively. The remaining five data entry fields relate to **resources**, and includes the labour levels, performance outputs and slab cycle time. The resource quantities are utilised by the algorithm in the calculation of the task druations with the user ultimately retaining control, free to enter a figure of choice. These fields are populated automatically when the form is opened with the mean values from the data base, that is, the average outputs and work group sizes for carpenters and steel fixers. This step permits the user to choose the average outputs achieved, or to adjust the output levels according to labour skill levels, logistics, location and other project specific constraints.

When the user has completed the data entry and clicked on the 'Add this Pour' button, Step 4 of the TDPA is completed and Step 5 is initialised automatically. Here, a sequence of code perfroms calculations on the data, predicting the durations for the formwork, reinforcement and SCT for the pour under review, refer to Figure 9-16 below.

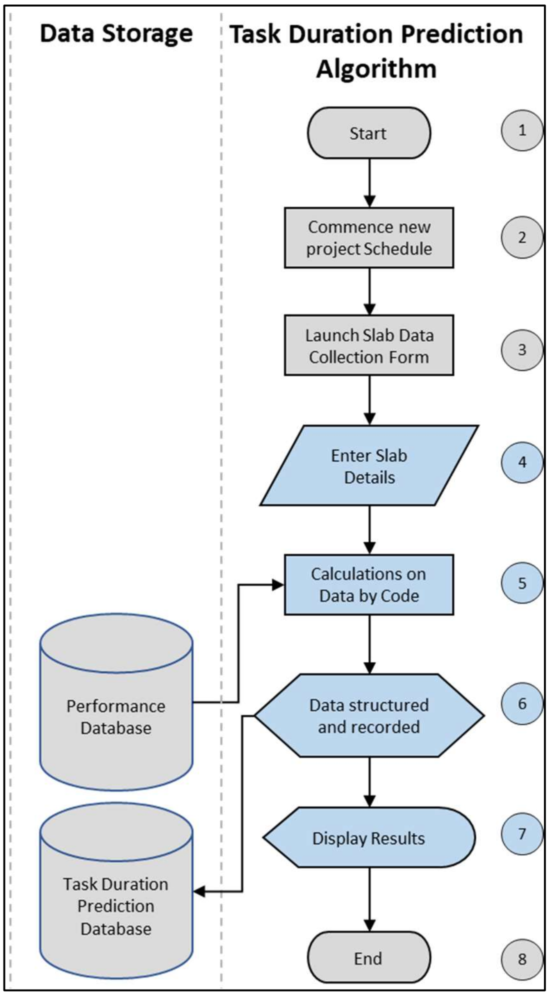


Figure 9-16. Steps 4, 5, 6 and 7 of the TDPA

TDPA Step 6 then transfers the results to the spreadsheet where it may be inspected by the user for veracity, in Step 7. The durations are available for use in proprietary planning software such as Asta PowerProject, Primavera P6, Microdsoft Project and so forth, with the user reatining control over the predictions. However, if alterations are required, the user must re-enter the pour details using the form, as the main body of the Excel spreadsheet does not contain formulae and will not re-calculate the durations, the calculations are contained in the VB code. This is purposeful; the rationale is to maintian the robustness of the algorithm and the code, preventing accidental manipulation of the data. This requriement is clearly indicated on the spreadsheet as illustrated in the extract shown in above.

As with the Data Collection algrithm, the text entry boxes are cleared of data and returned to blank fields for the next occasion the form is initialised. In addition, similar message boxes are displayed if the user enters partial details and attempts to add the data to the spreadsheet, as this would prevent the successful execution of the algorithm. The code for both of these operations is very similar to that described previously for the Data Collection algorithm. As indicated above, the output values and labour levels for carpenters and steel fixers are extracted from the knowledge database and displayed on the form.

When the form is completed, the user clicks on the ‘Add this Pour’ button. The form will close when the ‘Close’ button is selected, otherwise the form remains open, with the form fields cleared of data in preparation of a subsequent set of details for another slab pour. The process is repeated as required, populating the spreadsheet with pour data and duration calculations. When the user views the spreadsheet, the duration predictions are available for use, highlighted in red column headings. It is noted that the algorithms can be used independently of each other, as the database is also a useful tool to montior progress, whilst the duration collection algorithm can provide the user with formwork height, quantities of reinforcement and formwork as well as concrete volumes.

9.3.3 Task Duration Prediction Code

This section presents the code compiled to analyse the collected production data and perform predictions automatically on the duration of the formwork, reinforcement and SCT durations. The code was compiled in Visual Basic and follows, in principle, the structure of the PDCA, requesting data in a form, executing calculations on that data and displaying it in a spreadsheet.

The TDPA code also contains a calculation to determine the height of the formwork, which is performed by subtracting the slab thickness from the structural slab level, or SSL, to give the soffit level of the slab in question, with the difference in level to the slab below being the height of the formwork. To maintain consistent units in the calculation, the slab thickness, normally provided by the structural engineer in mm, is divided by 1,000 to give metres which are the same units normally used for SSL values. The SSL of the slab below is then subtracted from the slab soffit level, giving the database value ‘Height of Formwork’, as previously identified in *Equation 2-5*.

The volume of concrete is calculated by finding the product of the slab thickness and the area, as shown previously in *Equation 2-3*. When the volume of concrete has been calculated in cubic metres, this value is then multiplied by the density of reinforcement, which is expressed by structural engineers as kg/m^3, or kilograms of reinforcement steel per cubic metre of concrete. The result is the quantity of reinforcement in the slab, in kg, as found in *Equation 2-5*. When the mass of reinforcement is determined, the code uses this value to calculate the duration to install the reinforcement. This is done by taking the mass of the reinforcement and dividing it by the product of the quantity of steel fixers and the steel fixer output. Figure 9-17 below shows the geometric properties to the slab under consideration.

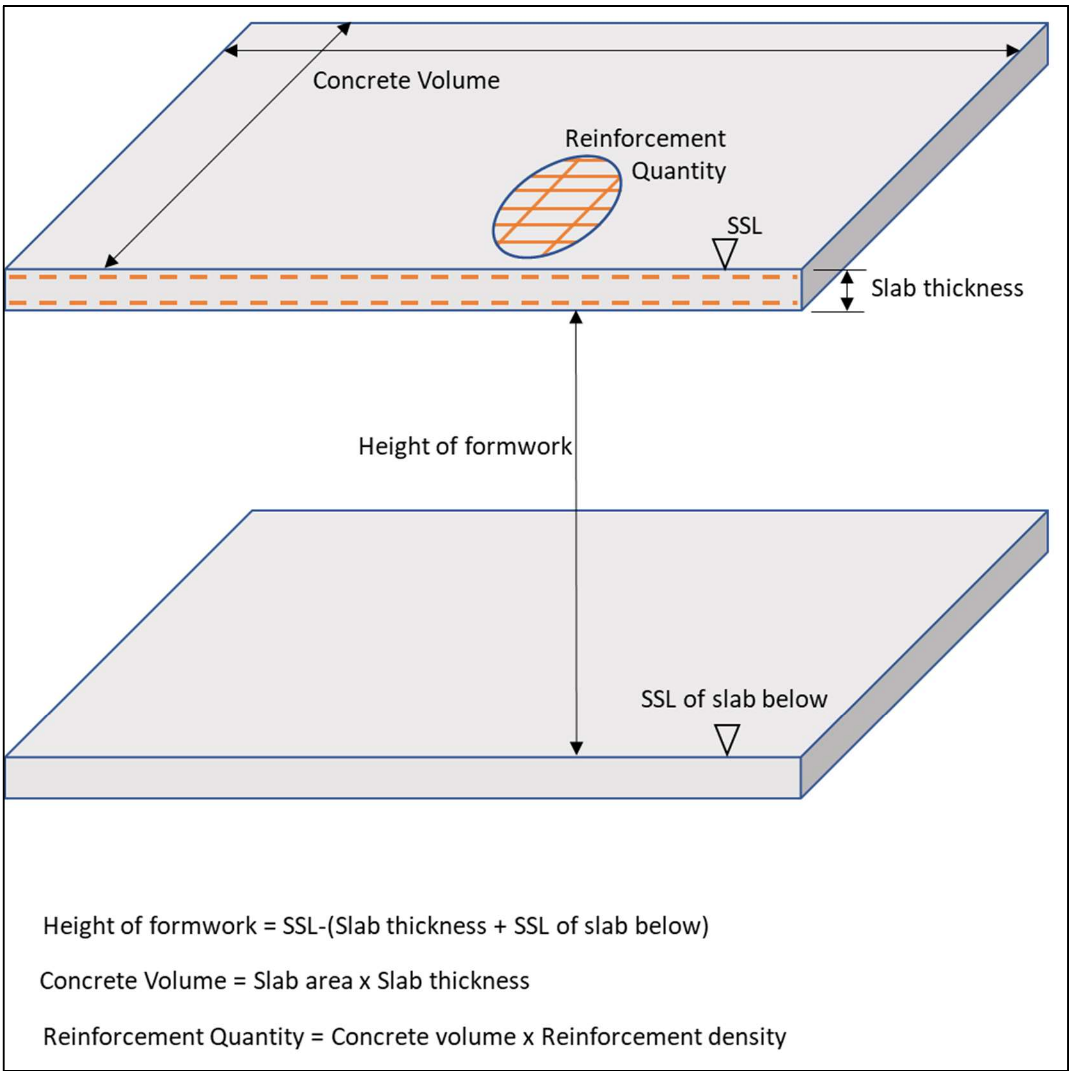


Figure 9-17. Geometric properties used by the TDPA to calculate required output

The adjusted Correlation Coefficient, RA2, from *Equation 4-6* is found for each task duration and slab cycle time automatically in the spreadsheet, producing the RA2 values as shown in Figure 9-10 and above. When the RA2 coefficients of correlation are determined, they are used to augment the original estimate of output made by the planner automatically, employing *Equation 4-7* above and the MAD values as described in *Equation 4-2* and *Equation 4-3*, presenting the user with a predicted duration for the slab pour under consideration. As indicated in the state-of-the-art planning review in Chapter 2, the resulting duration is frequently a fraction of a day, so the duration is rounded-up by the code to the nearest full day as outlined in *Equation 2-6*.

Whilst the output from Calchas is based on the collection of data from standard, flat RC slabs, it is possible to use the duration prediction tool for other forms of construction. For example, post-tensioned concrete or slipform construction or stepped slabs of varying thicknesses could be easily incorporated through the introduction of additional form fields in the PDCA and TDPA forms. These additional form fields would then be linked to additional columns in the database and be subjected to MAD and Modified Pearson's R calculations similar to those for RC flat slabs, allowing the prediction of future task durations.

9.4 Validation

Validation of the tool was initially achieved through the performance of a series of tests, following which Calchas was presented to the planning department of one of the largest contractors in the UK where it is currently being trialled.

9.4.1 Efficacy of Calchas

The PDCA and TDPA were developed to collect and store data and provide task duration predictions for the formwork and reinforcement installation. In order to interrogate the veracity and robustness of the algorithm coding and identify any shortcomings, positive outcomes and limitations, a series of tests were undertaken as follows:

- **Test Set 1: Initial Testing**

The first set of tests involved populating the knowledge database with typical performance data, ensuring that the macros and code commands were executed satisfactorily, and the subsequent calculations were performed correctly. Similarly, testing was carried out on the task duration prediction algorithm to interrogate the accuracy of the results, checking them against independent calculations. Please refer to Appendix G for a table of the independent verification calculations.

- **Test Set 2: Task Duration Prediction Algorithm**

Further testing was performed on the six schedules analysed in Chapter 7 above, using the TDPA to forecast the durations of the reinforcement and concrete tasks. In the absence of extensive project data, the predictions were based on the baseline durations in the database and were performed using the actual values for the steel fixer and carpenter labour levels and materials utilised on site, allowing a direct comparison. The as-constructed data, as outlined in Table 7-3 and Table 7-6, includes details of the reinforcement and formwork outputs and labour levels utilised on site. The TDPA was initialised from the Task Duration Prediction spreadsheet and the form was completed for each of the six projects, A to F, using the as-built data for the formwork and reinforcement quantities and labour levels. The differences between the as-constructed data and the durations predicted by the algorithm for the six projects were then compared.

It was found that the predictions offered by the algorithm were close to the actual task durations for formwork, but less accurate for reinforcement and slab cycle times. Four out of the six projects were more accurately predicted for the formwork durations as shown in Figure 9-18, where the predicted duration error was reduced by an average of 9%.

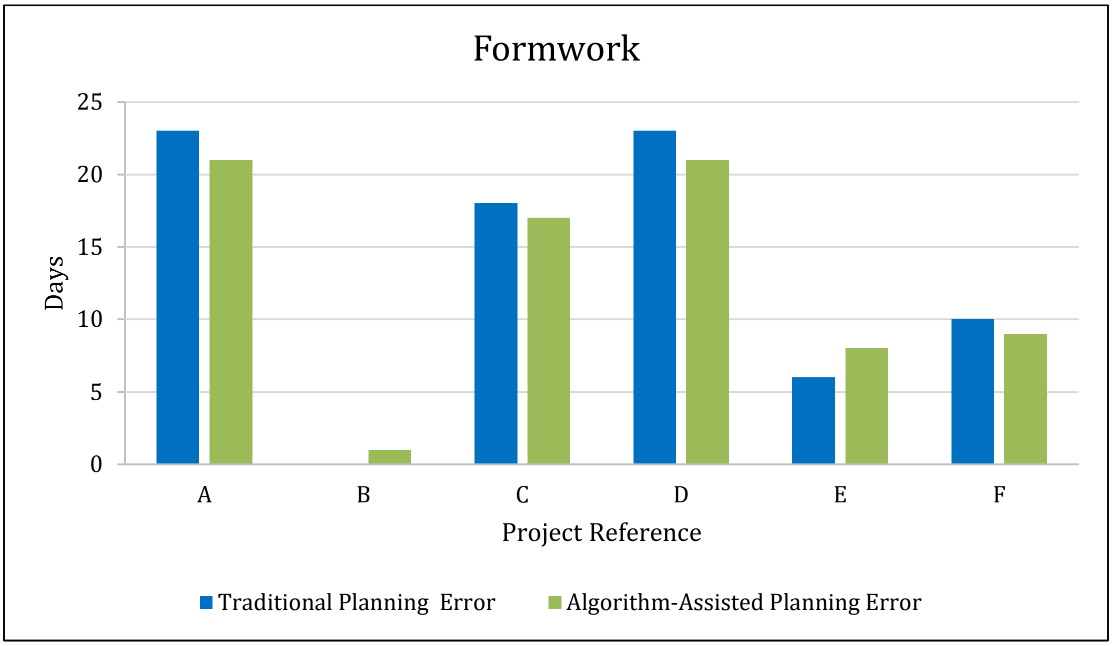


Figure 9-18. Traditional and Algorithm-Assisted Formwork Duration Errors

For Project B, the as-built data shows that the actual duration was equal to the planned duration, although the algorithm predicted that the task would take 1 day longer than planned, as, based on the output performance experienced in other projects it was expected to have a longer duration. Project E is a similar case where the algorithm predicted duration was longer (and less accurate) than the actual duration estimation error. It can be seen from the data tables above that the RA2 value used in the determination of the corrections increased the durations, as it is a positive number. Where the actual durations have been shorter or equal to the planned, the algorithm predicts that the duration will be longer, demonstrating a greater error than the traditional duration prediction.

For the predicted reinforcement duration, it can be seen in Figure 9-19 that the RA2 value was found to be 1. This is because the planned and actual durations were very similar, resulting in very small average deviation values, or errors, with the modified correlation coefficient, RA2, calculated to be 1. It is also noted that the actual durations are shorter than the planned duration for Projects B, D and E, whilst Project C remained constant. It is therefore possible that the quantity of steel fixers or reinforcement quantity fluctuated during the construction period, affecting the productivity levels, although the complete records are not available for inspection to disprove this. Calchas has been designed to overcome these uncertainties by requesting labour levels from the user, allowing more accurate output levels to be recorded. This permits continual expansion of the database and consequently enhanced accuracy of task duration predictions.

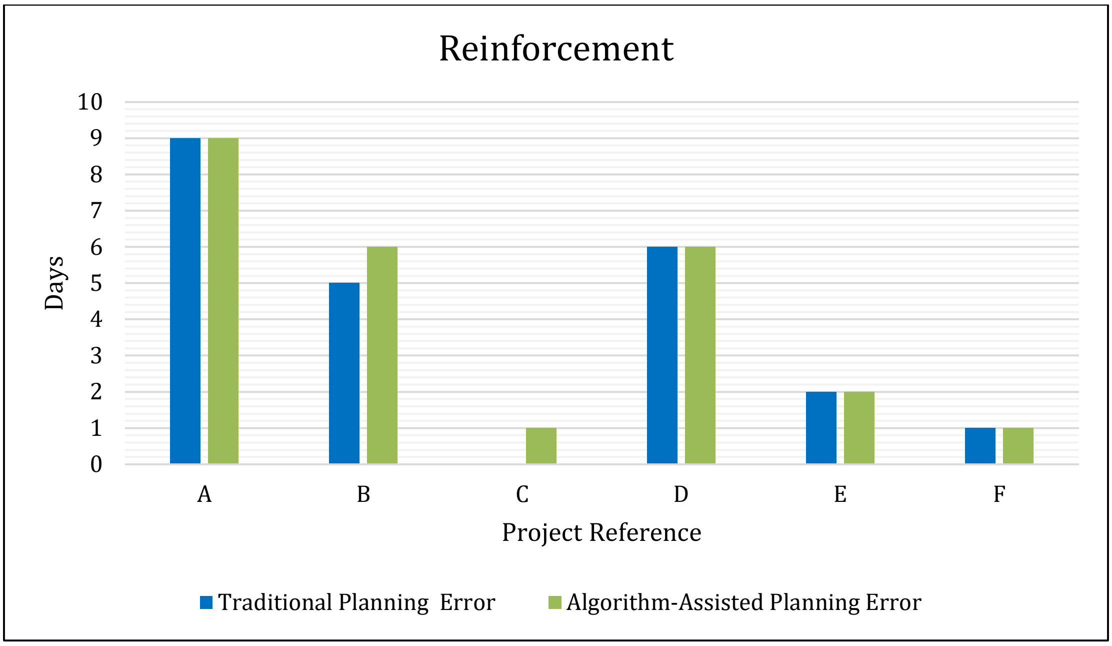


Figure 9-19. Traditional and Algorithm Reinforcement Duration Errors

In common with the reinforcement findings, the RA2 value for the SCT was also found to be 1, with no augmentation of the user's estimate required, as illustrated in Figure 9-20. It is also expected that this would change as the database expands through use.

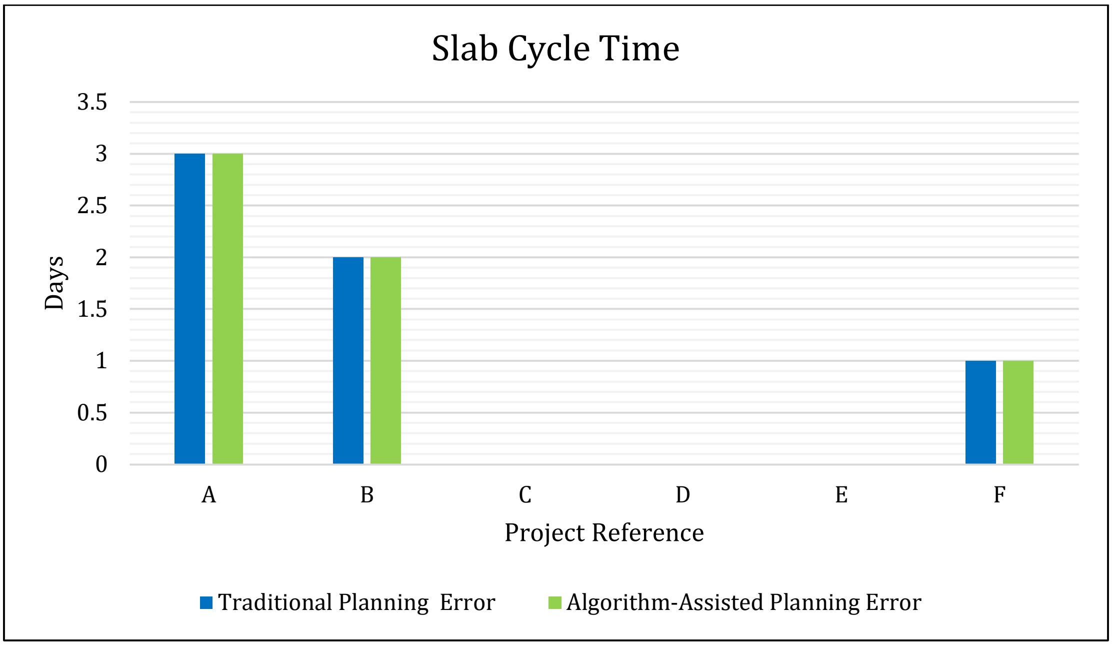


Figure 9-20. Traditional and Algorithm-Assisted SCT Duration Errors

Therefore, the results of actual performance in the database indicated that the planned SCT's were very close to what was actually achieved, with only three projects, A, B and F, demonstrating a change in duration from what was planned, as shown in Table 9-2 below.

Table 9-2. Comparison of the as-built and predicted durations.

		Schedule Reference					
		A	B	C	D	E	F
Formwork	Planned Duration (days)	190	148	115	275	200	120
	Actual Duration (days)	213	148	133	298	194	130
	Difference between Planned and Actual (days)	**23**	**0**	**18**	**23**	**6**	**10**
	Predicted Duration (days)	192	149	116	277	202	121
	Difference between Predicted and Actual (days)	**21**	**1**	**17**	**21**	**8**	**9**
Reinforcement	Planned Duration (days)	175	130	98	235	120	84
	Actual Duration (days)	184	125	98	229	118	85
	Difference between Planned and Actual (days)	**9**	**5**	**0**	**6**	**2**	**1**
	Predicted Duration (days)	175	131	99	235	120	84
	Difference between Predicted and Actual (days)	**9**	**6**	**1**	**6**	**2**	**1**
Slab Cycle Time	Planned SCT (days)	12	12	10	6	7	8
	Actual SCT (days)	9	10	10	6	7	7
	Difference between Planned and Actual (days)	**3**	**2**	**0**	**0**	**0**	**1**
	Predicted SCT (days)	12	10	10	6	7	8
	Difference between Predicted and Actual (days)	**3**	**2**	**0**	**0**	**0**	**1**

- **Test Set 3: Industry Testing**

Testing in the field has also taken place by planners in the planning department of one of the largest civil engineering contractors in the UK, where it has been well received, with positive feedback provided by the senior planner using the tool (please see Appendix E). The company collects the necessary performance data already through alternative platforms including weekly progress reports and schedule droplines, similar to other organisations as discussed in the state-of-the-art review in Chapter 2 above. However, whilst the data has been collected, it has historically not been collated and analysed to improve perfromance predictions, it is only used for the purposes of identifying projects which are falling behind schedule. The Senior Planner is pleased to employ the data already collected to drive increased forecasting accuracy and has found Calchas to function successfully when creating tender schedules. Whilst it is noted that since the trial has commenced, the projects which have been tendered for have yet to begin, however the tool is performing as expected during the pre-construciton phase and provides, in the view of the users, ease and speed of task duration prediction.

9.4.2 Limitations of Use

There are a number of limitations with using Calchas, discovered through the processes of compiling and testing. Firstly, it is imperative that the data collection and prediction algorithms are used for the purpose intended, that is, to predict the duration of formwork and reinforcement installation durations for suspended floor slabs in reinforced concrete frames. The coding has not been compiled to take into account floor slabs with steps, slopes, chamfers, folds, down-stand beams, thickenings or other features; it is assumed that slabs are flat, have a constant thickness and are constructed in a standard manner using standard materials and equipment typically found in the United Kingdom. It is also assumed that the reinforcement is loose steel reinforcement bar to British Standard BS8666 (British Standards Institution, 2005), as the output rates are different for other types of reinforcement, such as welded mesh or stainless steel, for example. It is noted that the output rates are based on a skilled labour force, experienced in carpentry and steel fixing and are gathered from projects within the Greater London area.

Alternative construction methods have not been considered, such as post-tensioned concrete floor slabs, or composite slabs, where the reinforcement is typically of a lower density. In these instances, the user should make allowances for the change in output rates. In addition, there is evidence to suggest that the height and type of formwork will affect the erection speed, but this has not been taken into account due to insufficient data. However, provision has been made in the data collection form and database to collect and store formwork type and height data when it becomes available, permitting the future introduction of additional categories to the data prediction algorithm. The data entry form has been amended to offer the user a choice of formwork category and height and the Visual Basic code and spreadsheet layouts can be enhanced to encompass additional categories as required. Notwithstanding the forgoing provisions, the task duration prediction will be suitable for any location or work force skill level as the ongoing collection of performance data (that is, reference classes) in any particular category will provide the user with increasingly accurate results.

It noted also that the use of a tool for a new company with no performance history will require the collection of performance data to create a database, prior to full implementation of the tool. In the absence of specific output data, the planner will develop schedules through their own means. The PDCA can be used to collect project performance data across the new organisation creating a project performance database. As the quantity of reference classes increases, the accuracy of the task duration predictions will be enhanced through he use of the TDPA and the full implementation of the tool.

9.5 Summary

This chapter has described the structure of the knowledge database, explaining how data and information is displayed and why and how the baseline production rates were chosen. The code to populate the database was then highlighted, including a description of the data entry form and the user entry fields therein. The data prediction algorithm was then discussed, outlining the task duration prediction spreadsheet and the data input form. The code underpinning the form was then described, followed by a discussion identifying the limitations of the data prediction process.

Testing has also been carreid out on Calchas in three phases – during compilation to assess the rigour of the code, on six historic scheudles, and currently ongoing in the field, where the tool has been found to be beneficial in an industrial setting. This testing has confirmed proof of concept and shown that the tool provides increased accuracy in the prediction of task durations.

10 Conclusions and Recommendations

10.1 Construction Project Management

It is evident from a review of construction project management literature that there is a requirement to enhance the accuracy of construction schedules, including those associated with RC frames. This is corroborated by the questionnaire survey results and practitioner interviews, as well as the schedule performance of a number of recent construction projects. There are a number of different methods which may be used to compile construction schedules, but all schedules rely on a prediction of the duration of each task. There is consensus in literature, both within the project management paradigm and beyond, that the duration of tasks may be estimated based on the duration of similar tasks accomplished previously. Professional practice, as evidenced by the questionnaire survey results, is aligned with the concept of applying task durations based on past performance when developing a project schedule, where the planner augments durations by making allowances for specific project constraints.

Significantly, it was found that even though some practitioners use published productivity data, they remain reliant on heuristics, rules of thumb and intuition to derive estimates of task durations. These estimates are founded on memories of past events, and, as highlighted in Chapter 2, human beings' conceptualisations based on memories of past events are unreliable, suffering from what is termed memory bias. This cognitive bias may be overcome by using a technique known as RCF, where data on past performance is collected and used to predict construction project outcomes. This method of enhancing the decision-making process when faced with uncertainty (that is, RCF) has proved to be an effective tool for reducing the incidence of overruns in large infrastructure projects.

This research has found that the process of RCF may be reduced into a series of mathematical equations, lending itself to be structured as an algorithm and scripted as VB code. Subsequently, a tool was developed where productivity data is entered by the user into a form and ultimately offers predictions for future task durations based on statistical analysis. In a novel approach, Chapter 3 identified a unique method of applying statistical analysis to the productivity data using the Mean Absolute Deviation calculation in place of the typical standard deviation, thereby taking outlying data points into account without enhancing the error impact as standard deviation can.

To facilitate the use of RCF, suitable classes of data to form the reference base must first be gathered, with projections becoming more accurate as a history of performance data is developed for individual organisations, as each will perform slightly differently. To enable this requirement, a series of VB code was developed, as explained in Chapter 9, to gather productivity data through an enquiry form, something which has been successfully used in practice.

10.2 Production Data

One particular challenge highlighted by the interviews and questionnaire results is the inconsistent frequency of progress measurement, where it is measured and recorded at intervals varying from daily through to monthly, or longer. Calchas, the tool proposed by this research, prompts the users to complete data collection weekly, as the majority of project staff measure progress at this frequency. In the questionnaire survey, respondents also indicated a range of productivity estimates, indicating a variation across the industry, supporting the argument for a need to record and understand clearly the productivity achieved on site.

Production data is therefore collected from site staff through a data collection form, which has been designed to gather salient productivity data from RC frame projects and upload it to a database. To facilitate compilation of the form and ease implementation by users, the tool has been established in Excel with the data collection element coded, as previously indicated, in Visual Basic. The user interface consists of a button in a spreadsheet which, when selected, displays a pop-up form in a new window. The form has a number text-boxes where the user is required to enter variables relating to productivity, such as ‘gang’ or crew size and the outputs achieved during the week, including quantities of formwork erected and reinforcement installed, whilst the formwork properties, such as type and height, of each slab pour are also required on the data collection form, permitting further automated calculations on the data.

10.3 Database

In addition to the collection of the productivity data, it must also be stored in a manner suitable for re-use. Therefore, when the data entry is complete, the process has been automated within the VB coding where the data is transferred from the user form to the Excel database, populating a spreadsheet of salient data. The form entries are used to calculate additional information where the embedded code determines metrics such as the productivity of the carpenters and steel fixers, the slab-to-soffit height, as well as other calculations including the slab cycle time, volumes of concrete and mass of reinforcement. The database also advises the user of the shortcomings in project performance with a traffic-light warning system, as well as advising, for example, where additional resources or work methods should be considered to improve performance.

10.4 Data Usage

This research has been carried out at a time when there is increasing pressures on profit margins, with tightening project budgets and productivity demands stretched more than ever and the performance of site labour is under increasing analysis, in particular since the Covid-19 crisis manifested in the UK in Q1 2020. The value of construction project starts fell by a significant amount in the second quarter of 2020, and as the crisis continues the full ramifications remain to be realised. Against this backdrop of uncertainty, and despite being in a period of disruptive technological advances, productivity in the construction industry has not kept pace with increases in productivity in other industries. With this in mind, Calchas, the performance tool proposed in this research, enables project managers and planners to record productivity and provide valuable data, facilitating more accurate planning and scheduling, advancing towards construction schedule certainty. It also provides real-time feedback on the performance of their project in comparison with the others in their organisation, highlighting areas for improvement and suggesting corrective actions. Furthermore, Calchas allows planners to enter geometric data for slab pours under review and receive predictions of task durations.

10.5 Gap in Practice

The gap in practice was identified in Chapter 2 as how to schedule correctly, manifesting as a difference between planned project task durations and those actually achieved. The results of the questionnaire survey highlighted an acknowledgement from practitioners that construction schedules are prone to inaccuracy, with the vast majority of respondents confirming that task duration forecasts could be improved. It has been shown that by improving the measurement and recording of progress, durations can be more accurately predicted for formwork erection, reinforcement installation and SCT, through the use of RCF. To manage the implementation and ongoing use of RCF, the VB coding linked to an Excel database have effectively provided a tool which is simple to use for both data collection and use.

10.6 Responses to Research Objectives

This research proposed that the collection and analysis of production data will enhance the accuracy of construction schedule predictions; following the fulfilment of the research objectives, it is held that this proposal has been proven.

Table 10-1. Research Objectives and Responses

Research Objectives	Responses
RO1 To understand the state-of-the-art of scheduling practices in the UK.	Current professional practice involves compiling construction schedules using a number of different resources, but has been found to ultimately rely on heuristics based on inaccurate memories of past events, rather than verified published data. The majority of survey respondents acknowledge that construction schedules could be more accurate, but continue to calculate task durations inaccurately.
RO2 To critically review the current scheduling practices in the UK.	Planning and scheduling in construction can be enhanced through the use of a knowledge management system, where historic performance data is analysed using RCF, which can be enhanced through statistically analysing data using the Median Average Deviation calculation.
RO3 To investigate site productivity	Site productivity rates have been investigated, with typical values achieved as follows: - Formwork: 9.3m^2/carpenter/day - Reinforcement: 925kg/steel fixer/day - Slab Cycle Time: 9 days
RO4 To develop and validate a tool to improve construction schedule accuracy	A tool, Calchas, has been developed which collects performance data from site inputs. The accuracy of task duration predictions is then improved, based on historic performance.

10.7 Research Problem and Aim

The research problem was outlined in Chapter 2 as how the creation of inaccurate construction schedules can be overcome, with the aim of this thesis identified as the development of a novel tool to enhance project management by improving schedule accuracy in RC frame buildings. The research problem has been answered, and the aim has been achieved, through the development of Calchas, a novel tool for construction project managers and planners. Calchas is simple to use and requires very little training, where the user enters performance data weekly which the tool then statistically analyses, predicting RC frame task durations with enhanced accuracy.

10.8 Response to Central Question

The invention of Calchas is a means to investigate, explain and propose ways forward in response to the central research question identified in Chapter 1: 'how the creation of inaccurate construction schedules can be overcome.' Deficiencies in current planning practice were established in the literature review in Chapter 3 and further confirmed through analysis of the research data, where participants confirmed they predominately use rules of thumb and heuristics when planning construction projects. Calchas offers an alternative method to evaluate task durations, exploiting geometric data from the proposed structure to determine the quantity of work to be done, with the knowledge database of historic outputs used to indicate the most likely duration to complete that task.

10.9 Contribution to Practice and Knowledge

Calchas is underpinned by a database of construction site productivity which is informed through a novel algorithm, the PDCA which, when initialised, presents a form for the user to enter productivity data related to the productivity achieved on site, as well as data regarding the type of formwork and the geometric properties of the RC floors constructed in the preceding week. This data is then decanted into the database spreadsheet in a pre-determined structure. A second algorithm, the TDPA, permits the user, when developing a construction schedule for an RC frame, to enter the geometric data and predicted labour levels for the RC floor under consideration. Using the entered data, the TDPA performs calculations on the performance data in the database and provides a forecast for the duration of formwork erection, the reinforcement installation and the slab cycle time. It has been found to successfully predict with greater accuracy the duration for formwork installation with limited baseline data. The predictions for reinforcement installation and slab cycle times were found to offer no improvement in the prediction, however it is expected that as the database of reference classes expands the predictions will become more pronounced, offering increased accuracy.

Calchas has a number of novel aspects, including the following:

- Typically, RCF is a macro approach to forecasting, where the duration and cost of megaprojects such as the Olympic Games, railway lines, bridges and tunnels are investigated. This research has developed a new RCF process for task duration in RC frame construction which is a novel application of RCF in a micro scale.

- Novel equations for calculating RCF, where previously an estimate of accuracy was made by the user, the accuracy estimate is now controlled statistically by the Modified R value.
- The performance and rigour of the calculations undertaken offer a novel process to enhance the prediction of task durations in RC frame construction.
- A novel database of productivity has been developed. Up to this point, the data was varied and not structured to any significant degree; the database is based on data collected from the field rather than rules of thumb and heuristics and stored in a structured manner.
- A pair of novel algorithms has been developed, culminating in the use of the novel duration prediction equation.
- The database will grow very quickly, as it is expanded weekly by the addition of data from every project within an organisation.
- Calchas also has the potential to change behaviour of users, as reflection and analysis of productivity will be espoused through the use of the tool.
- The code used to develop Calchas may be manipulated easily to manage data from alternative forms of construction, such as post-tensioned concrete, tunnel form or slipform, for example, or almost any construction process where reference classes can be established.
- This research paves the way for machine learning and artificial intelligence to be utilised in the prediction of construction schedules, as the predictions in this research can be automated, with the algorithm learning from the constantly expanding database.

10.10 Recommendations for Future Research Avenues

It is recognised that whilst this research has developed a process to enhance schedule accuracy, some areas remain unexplored which are worthy of investigation and further research, with the potential to develop and broaden the scope of the duration prediction tool. The first recommendation is to expand the database through the inclusion of additional categories, such as formwork height (as discussed in Chapter 9), alternative forms of construction such as post-tensioned concrete, beam and slab designs, slip form cores, tunnel form buildings or the inclusion of crane data. For example, it is considered that incorporating crane data into the database could provide insight into the interdependency of production rates and the type and capacity of crane supplied, as it was found in Chapter 8 and experienced in practice, cranes have a critical impact on progress. Furthermore, is believed that any measurable metric which affects the production rate of construction can be included in the database, although caution should be exercised in deciding precisely what data to collect and how it is blended to ensure relevance and structure in any future reference class.

It is also recommended that further trials are undertaken on the algorithm and associated code by utilising it for a number of projects throughout their lifecycle. This would provide the ability to evaluate slab pours in further detail, as each task could be scrutinised and evaluated for the expected increase in accuracy. Promoting the use of Calchas would be a challenge, as the industry remains notoriously slow to adopt new ideas, in particular as the increase in accuracy may often include an increase in tender schedule duration and be perceived as influencing tender bids to be less competitive. However, transparency of the process to develop the schedule output rates will encourage clients to trust the proposed tender duration, enhancing the competitive offering. Furthermore, to overcome contractor apprehension, promotion of the tool could be obtained through a demonstration of the results achieved in this research, followed by trials in the field where comparisons between algorithm-predicted and traditional estimates are made, demonstrating the increase in accuracy.

It is also anticipated that the data gathered during the construction phase of a project could be introduced into the BIM model which may be capitalised on to develop more accurate schedule predictions during the construction of the scheme or future adaptions to the structure, including alterations and demolition. It is also an aspiration that a comprehensive library of resource would be created, allowing the data and information to be drawn upon for decision making regarding the planning and scheduling of future projects.

Finally, it is notable that although further data existed relating to the projects analysed in Chapter 7 above, the outbreak of corona virus (COVID-19) in the UK in 2020 meant that the researcher no longer had access to the data. It is therefore recommended that deeper analysis would be possible by future researchers who have unrestricted access to site progress data.

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12 Appendices

Appendix A: Questionnaire Survey

Key:

- o Select one answer
- ☐ Select all answers that apply

Q1. Please confirm your age group

- ○ 18 to 24
- ○ 25 to 34
- ○ 35 to 44
- ○ 45 to 54
- ○ 55 to 64
- ○ 65 to 74
- ○ 75 or older

Q2. Please indicate how long you have been working in the construction industry:

- ○ 0 - 1 year
- ○ 2 - 5 years
- ○ 6 - 10 years
- ○ 11 - 15 years
- ○ 15 years and above

Q3. Please state your current job title below:

Q4. What is the highest level of education you have completed?

- ○ No formal education
- ○ School
- ○ Entry Level Award
- ○ Level 1: NVQ Level 1
- ○ Level 2: CSE/GCSE/O Level, NVQ Level 2
- ○ Level 3: A/AS level, NVQ Level 3
- ○ Level 4: Certificate, NVQ Level 4
- ○ Level 5: HND, NVQ Level 5
- ○ Level 6: Bachelor's Degree, NVQ Level 6
- ○ Level 7: Masters' Degree, NVQ Level 7 ☐

- Level 8: Doctorate (such as PhD, DEng)
- Other (please specify)

Q5. Please indicate your professional membership(s). Select all that apply.

- ☐ CIOB
- ☐ RICS
- ☐ RIBA
- ☐ ICE
- ☐ IStructE
- ☐ APM
- ☐ Other (please specify)

Q6. Do you assess progress in RC frame projects?

Yes / No

Q7. In your opinion, to what extent does the progress of the reinforced concrete frame influence the overall project progress?

- Very strong influence
- Strong influence
- Neutral
- Little influence
- Very little influence

Q8. Progress measurement is typically an ongoing process. How frequently do you think progress should be measured?

- Every day
- A few times a week
- About once a week
- A few times a month
- Once a month
- Less than once a month
- Never
- Other (please specify)

Q9. How do you think progress of the concrete frame should be determined?

- Observation – a visual inspection of the work completed

- Measurement – a measurement or a calculation of the amount, such as Tonnes or cubic metres
- Observation and Measurement - a combination of these two methods
- Other (please specify)

Q10. The previous question related to how you think progress should be determined. In your opinion, how effective are the measurement methods?

- Extremely effective
- Very effective
- Somewhat effective
- Not so effective
- Not at all effective

Q11. In your opinion, to what extent does the progress of the reinforced concrete frame influence the overall project progress?

- Very strong influence
- Strong influence
- Neutral
- Little influence
- Very little influence

Q12. Progress measurement is typically an ongoing process. How frequently do you usually measure progress?

- Every day
- A few times a week
- About once a week
- A few times a month
- Once a month
- Less than once a month
- Never
- Other (please specify)

Q13. How do you normally determine progress of the concrete frame?

Observation – a visual inspection of the work completed

- Measurement – a measurement or a calculation of the amount, such as Tonnes or cubic metres
- Observation and Measurement - a combination of these two methods
- Other (please specify)

Q14. The previous question related to how you determine progress. In your opinion, how effective are the methods you use?

- Extremely effective
- Very effective
- Somewhat effective
- Not so effective
- Not at all effective

Q15. When determining progress in RC frame construction, what type of data do you think should be consulted? This could be volume of concrete, for example, or the amount of a particular task completed, such as area of formwork erected, or number of floors completed.

Q16. When determining progress, it is considered by some that any method used should be accurate. In your opinion, how accurate are the methods used?

- Extremely accurate
- Very accurate
- Somewhat accurate
- Not so accurate
- Not at all accurate

Q17. When determining progress in RC frame construction, what type of data do you consult? This could be volume of concrete, for example, or the amount of a particular task completed, such as area of formwork erected, or number of floors completed.

Q18. Please rank the following from 1 to 5, with 1 being the most important, in terms of how important they are to your calculation or estimation of progress.

1. Reinforcement fixed in position
2. Concrete placed
3. Falsework / formwork erected
4. Vertical members erected (walls, columns etc.)
5. Feeling or instinct

Q19. One measurement of progress in constructing suspended slabs is the rate of erection of falsework and formwork. Please estimate how much

traditional falsework and formwork would you expect to be erected per day per carpenter?

Q20. Progress may also be influenced by the rate of installation of reinforcement. Please estimate, in kg, how much reinforcement you would expect to be installed per day per steel fixer, assuming an average bar diameter of 16mm.

Q21. Progress can be influenced by the length of time to complete each successive slab pour, including the walls and columns supporting the slab, falsework/formwork, reinforcement and concrete. Please estimate in days the length of time you expect it would take to complete a typical slab pour from start to finish.

Q22. When determining progress, it is considered by some that any method used should be accurate. In your opinion, how accurate are the methods you use?

- Extremely accurate
- Very accurate
- Somewhat accurate
- Not so accurate
- Not at all accurate

Q23. Please rank the following from 1 to 5, with 1 being the most important, in terms of how important you think they are to calculating or estimating progress in RC frame construction.

1. Reinforcement fixed in position
2. Concrete placed
3. Falsework / formwork erected
4. Vertical members erected (walls, columns etc.)
5. Feeling or instinct

Q24. If you were to create a programme for a project with a concrete frame, how would you decide on the production rates, or the rate at which work is completed, for particular tasks? Please select all that apply.

- ☐ Experience and intuition
- ☐ Rules-of-thumb
- ☐ Consult colleagues
- ☐ Consult specialist contractors

- ☐ Industry publications and guidance, such as Spons or RICS
- ☐ Consult programmes from other similar projects
- ☐ Other (please specify)

Q25. 'Accurate knowledge of past performance will increase future programming accuracy'. Do you agree with this statement?

- o Strongly agree
- o Agree
- o Neither agree nor disagree
- o Disagree
- o Strongly disagree

Appendix B: Ethics Approval Letter

Anglia Ruskin University

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Chelmsford campus
Bishop Hall Lane
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CM1 1SQ

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19/10/2018

Dear Barry,

Principal Investigator: Barry Talbot
SID: 1451242
Project Title: An Investigation into the development of a conceptual framework to enhance construction programme forecasting using accurate performance data in reinforced concrete frames (working title)
EBE SREP Reference: EB18-010

I am pleased to inform you that your ethics application has been ***approved subject to minor amendments*** by the School Research Ethics Panel (SREP) under the terms of Anglia Ruskin University's Research Ethics Policy (Dated 8 September 2016, Version 1.7). Please action the points below and submit to your academic supervisor for them to review.

All ethical risks associated with data collection have been described and appropriate mitigation measures identified for deployment. However, as this is action research it is important that consequential losses potentially associated with modification of 'normal employee behaviours' are not attributable to Anglia Ruskin per se but lie within the usual line-management responsibilities of the researcher within their normal jurisdiction. A letter on corporate headed paper should be issued by the researcher/line management to this effect to be lodged along with all ethics documents in the appendix of the final thesis: This must be enforced by the supervisory team.

It is your responsibility to ensure that you comply with Anglia Ruskin University's Research Ethics Policy and the Code of Practice for Applying for Ethical Approval at Anglia Ruskin University available at www.anglia.ac.uk/researchethics including the following.

- The procedure for submitting substantial amendments to the committee, should there be any changes to your research. You cannot implement these amendments until you have received approval from SREP for them.
- The procedure for reporting accidents, adverse events and incidents.
- The Data Protection Act (1998) and General Data Protection Requirement from 25 May 2018.

Anglia Ruskin University

- Any other legislation relevant to your research. You must also ensure you are aware of any emerging legislation relating to your research and make any changes to your study (which you will need to obtain ethical approval for) to comply with this.

- Obtaining any further ethical approval required from the organisation or country (if not carrying out research in the UK) where you will be carrying the research out. This includes other Higher Education Institutions if you intend to carry out any research involving their students, staff or premises. Please ensure that you send the SREP copies of this documentation if required, prior to starting your research.

- Any laws of the country where you are carrying the research and obtaining any other approvals or permissions that are required.

- Any professional codes of conduct relating to research or requirements from your funding body (please note that for externally funded research, where the funding has been obtained via Anglia Ruskin University, a Project Risk Assessment must have been carried out prior to starting the research).

- Completing a Risk Assessment (Health and Safety) if required and updating this annually or if any aspects of your study change which affect this.

- Notifying the SREP Secretary when your study has ended.

Please also note that your research may be subject to monitoring.

Should you have any queries, please do not hesitate to contact me. May I wish you the best of luck with your research.

Yours sincerely,

Alan Coday
EBE SREP Chair

Appendix C: Interview Participant Information Sheet

PARTICIPANT INFORMATION GUIDANCE SHEET

Anglia Ruskin University

Section A: The Research Project

1. **Project Title**

   Working Title: A Conceptual Framework to Enhance Forecasting Using Accurate Historic Performance Data

2. **Brief summary of research.**

   The aim of this research is to develop a conceptual framework to enhance construction programming and forecasting using accurate performance big data in reinforced concrete (RC) frame structures. The target audience is those working in the construction industry with some knowledge of RC frame programming and progress assessment.

3. **Purpose of the study**

   I am a final year part-time researcher with the Faculty of Science and Engineering at Anglia Ruskin University where I am undertaking a PhD; I am also employed full-time as a Planning Manager with a leading UK construction contractor. Questionnaires and interviews will provide data to allow me to understand the opinions and practices of senior stakeholders regarding my area of study, forming answers to my research questions and the development of a framework to utilise historic data to inform future planning decisions.

4. **Who is supervising of this study?**

   Supervisor 1: Dr. Christian Henjewele, Senior Lecturer in Construction Project Management.
   Supervisor 2: Dr. Maryam Imani, Senior Lecturer in Engineering.
   Supervisor 3: Dr. Reuben Brambelby, Senior Lecturer in Civil Engineering.
   Advisor: Dr Georgios Kapogiannis, Assistant Professor in BIM, UNN, China.

5. **Why have I been asked to participate?**

   Participants have been selected as they are stakeholders affected by, or have an interest in, the scheduling and programming of reinforced concrete frame buildings.

6. **How many people will be asked to participate?**

   150 people will be requested to participate in interviews and questionnaires.

7. **What are the likely benefits of taking part?**

   It is unlikely that there will be any direct benefits to participants other than the knowledge that they are helping to advance knowledge and potentially improve the industry.

8. **Can I refuse to take part?**

   Participants can refuse to take part without giving a reason. Under no circumstances should participants feel coerced into taking part.

9. **Has the study got ethical approval?**

   The research has ethical approval from an ethics committee at Anglia Ruskin University.

10. **Has the organisation where you are carrying out the research given permission?**

Permission has been obtained to carry out this research. However, it is the decision of each person whether they would like to take part.

11. **Source of funding for the research, if applicable.**
    There is no third-party funding for this research. The researcher (Barry Talbot) is wholly funding it without contribution.
12. **What will happen to the results of the study?**
    The results will form part of a Doctorate Thesis and will be published in academic journals and presented at industry and academic conferences.

Contact for further information

If you have any concerns about how the study has been conducted, you may contact the Course Director of the Doctorate programme:

Dr. Alan Coday, Director of Professional Doctorate in Science & Engineering, Anglia Ruskin University, Bishop Hall Lane, Chelmsford, Essex, CM1 1SQ.

Tel: 01245 493 131

Email: Alan.Coday@anglia.ac.uk

Section B: Your Participation in the Research Project

1. **What will I be asked to do?**
   You will be asked to participate in a face-to-face interview, where the conversation will be recorded. You will be asked questions regarding your views on reinforced concrete frame construction and construction in particular. The aim is to determine how different stakeholders measure progress, how the process can be automated and how the collected data can be used to inform future planning and scheduling decisions.
2. **Will my participation in the study be kept confidential?**
   Participation in the research will be kept anonymous. The only people with access to the data will be the researcher. Participants' personal data will not be included in dissemination and the results will be written up in anonymised format. Whilst every attempt will be made to ensure anonymity, it may not be possible to guarantee complete anonymity as there is a slight chance that peers or colleagues may identify the participants.
3. **Use of quotes.**
   It is planned to quote from participants. Quotes will be anonymised but does increase the chance of participants being identified.
4. **Use of recording equipment.**
   Interviews will be recorded. The recording will be transcribed into text and the electronic version will then be deleted. The transcript will be held in a locked filing cabinet for a period of three years following completion of the study. It will then be destroyed.
5. **Will I be reimbursed travel expenses?**
   Participants will not be required to travel so will not incur travel expenses.
6. **Are Incentives offered?**

No incentives are offered to take part in the research.

7. **Are there any possible disadvantages or risks to taking part?**

   The risks of taking part are minimal. There is a risk of boredom, fatigue or participants becoming distressed, as well as risks to confidentiality. If participants experience any of these risks rest breaks or, in the case of serious effects, immediate termination of the interview. Agreement to participate in the study does not affect participant's legal rights.

8. **Whether I can withdraw at any time, and how**.

   Participants can withdraw from the study at any time and without giving a reason. This can be done via email to Barry.Talbot@pgr.anglia.ac.uk or by telephone or text to [redacted]. Participants will have the option to withdraw from the study and have their data removed, or to withdraw but permit the use any anonymised data that has been collected up to that point. The latest possible time to withdraw data will be 31/03/20 as after that point the data will be written-up and published. Participants do not have to answer any questions they do not wish to.

9. **Whether there are any special precautions you must take before, during or after taking part in the study.**

   If there is any information that participants may disclose that would need to be disclosed to someone else (e.g. if they are at risk or if anything is revealed of an illegal nature) then this information will be disclosed to the relevant authorities.

10. **What will happen to any information or data that are collected from you?**

    Interview transcripts will be held in a locked filing cabinet for a period of three years following completion of the study. It will then be destroyed.

11. **Will I see a copy of the interview transcript?**

    Following the interview, the transcript will be offered to the participants for verification. This will be done via email, where participants will be requested to confirm that the transcript is an accurate account of the interview.

12. **Will I see the results of the research?**

    All interview participants will be offered a summary of the research findings. The summary of the research findings will be sent via email to those requesting it.

13. **Contact details for complaints.**

    If participants have any complaints about the study, they are encouraged to speak to the researcher in the first instance via email to Barry.Talbot@pgr.anglia.ac.uk. Alternatively, participants can contact Anglia Ruskin University's regarding any complaints at complaints@anglia.ac.uk, postal address: Office of the Secretary and Clerk, Anglia Ruskin University, Bishop Hall Lane, Chelmsford, Essex, CM1 1SQ.

PARTICIPANTS ARE GIVEN A COPY OF THIS TO KEEP,
TOGETHER WITH ACOPY OF THE CONSENT FORM.

Date 27.05.18 Rev 5.0

Appendix D: Interview Participant Consent Form

PARTICIPANT CONSENT FORM

Anglia Ruskin University

NAME OF PARTICIPANT: ______________________

Project Title

A Conceptual Framework to Enhance Forecasting Using Accurate Historic Performance Data

Main investigator and contact details:
Barry Talbot, Doctorate Researcher, Anglia Ruskin University, Chelmsford, Essex CM1 1SQ.
Email: Barry.Talbot@pgr.anglia.ac.uk

Members of the research team:

Supervisor 1: Dr. Christian Henjewele, Senior Lecturer in Construction Project Management.

Supervisor 2: Dr. Maryam Imani, Senior Lecturer in Engineering.

Supervisor 3: Dr. Reuben Brambelby, Senior Lecturer in Civil Engineering.

Advisor: Dr Georgios Kapogiannis, Assistant Professor in BIM, UNN, China.

1. I agree to take part in the above research. I have read the Participant Information Sheet Rev.5.0 for the study. I understand what my role will be in this research, and all my questions have been answered to my satisfaction.
2. I understand that I am free to withdraw from the research at any time, without giving a reason.
3. I am free to ask any questions at any time before and during the study.
4. I understand what will happen to the data collected from me for the research.
5. I have been provided with a copy of this form and the Participant Information Sheet.
6. I understand that quotes from me will be used in the dissemination of the research.
7. I understand that the interview will be recorded.

Data Protection: I agree to the University[1] processing my personal data which I have supplied. I agree to the processing of such data for any purposes connected with the Research Project as outlined to me*

Name of participant (print)…………………………Signed…………………..…. Date………………

Name of person
witnessing consent (print)………………………….. Signed………………….. Date………………

PARTICIPANTS MUST BE GIVEN A COPY OF THIS FORM TO KEEP
ADD DATE AND VERSION NUMBER OF CONSENT FORM.

I WISH TO WITHDRAW FROM THIS STUDY.

If you wish to withdraw from the research, please speak directly to Barry Talbot or via email at Barry.Talbot@pgr.anglia.ac.uk. You do not have to give a reason for why you would like to withdraw. Please let Barry Talbot know if you are happy for him to use data collected from you to date in the write up and dissemination of the research.

Date 27.05.19
Rev. 3.0

[1] "The University" includes Anglia Ruskin University and its Associate Colleges.

Appendix E: User Feedback

From: Satya Gangboir
Sent: 27 November 2020 11:03
To: Barry Talbot
Cc: 84rryt@gmail.com
Subject: Calchas Programme Prediction

Hi Barry,

Firstly, thank you for allowing us to trial Calchas in the planning department. It has been beneficial in the forecasting of task durations, giving comfort in the knowledge that there is some science behind the process, rather than following old rules of thumb. I look forward to seeing how the predicted tender programmes stack-up against the progress we achieve on site, though this will take another 6 months or so before the first project commencement.

The most revealing thing is that we collect all of the information from site every week, to produce the progress droplines, but this data is then lost. Calchas allows us to gain further use from our progress data, so implementation should be fairly straightforward. I see the key is to create the database carefully so the reference class is drawn from correct information.

Well done on creating a useful, easy to use tool, it is something I hope we can take forward on an ongoing basis. Instinctively, it can only help us achieve greater forecasting accuracy, which is the key to planning and programming.

Regards

Satya Gangboir
Senior Planner
Midgard Ltd
www.midgard.ltd.uk

JRL MIDGARD

4 Elstree Way, Borehamwood, Hertfordshire, WD6 1RN
M: +44 7828266371

Appendix F: VB Code

```
Private Sub Add_Data_Click()
Dim iRow As Long
Dim ws As Worksheet
Set ws = Worksheets("Project Data")

'find first empty row in database
iRow = ws.Cells.Find(What:="*", SearchOrder:=xlRows,
SearchDirection:=xlPrevious, LookIn:=xlValues).Row + 1

'check for pour reference
If Trim(Me.txtPourRef.Value) = "" Then
  Me.txtPourRef.SetFocus
  MsgBox "Please enter a pour reference"
End If

'check for SSL value
If Trim(Me.txtSSL.Value) = "" Then
  Me.txtSSL.SetFocus
  MsgBox "Please enter the slab SSL"
End If

'check for slab thickness
If Trim(Me.txtThickness.Value) = "" Then
  Me.txtThickness.SetFocus
  MsgBox "Please enter the slab thickness"
End If

'check for Area value
If Trim(Me.txtArea.Value) = "" Then
  Me.txtArea.SetFocus
  MsgBox "Please enter the slab area"
End If

'check for Rebar Density value
If Trim(Me.txtRebarDensity.Value) = "" Then
  Me.txtRebarDensity.SetFocus
  MsgBox "Please enter the reinforcement density"
End If

'copy the data to the database
'perform calculations on the data to predict durations

With ws
'insert values from text boxes into database cells
  .Cells(iRow, 1).Value = Me.txtPourRef.Value
  .Cells(iRow, 2).Value = Me.txtSSL.Value
  .Cells(iRow, 3).Value = Me.txtSSLBelow.Value
  .Cells(iRow, 4).Value = Me.txtThickness.Value
  .Cells(iRow, 5).Value = Me.txtSSL.Value - (Me.txtThickness.Value / 1000)
  .Cells(iRow, 6).Value = (Me.txtSSL.Value - (Me.txtThickness.Value /
1000)) - Me.txtSSLBelow.Value
  .Cells(iRow, 7).Value = Me.txtArea.Value

  'Calculate the volume of concrete
     .Cells(iRow, 8).Value = ((Me.txtThickness.Value) / 1000) *
Me.txtArea.Value
```

```
  'Calculate the quantity of reinforcement in kg
     .Cells(iRow, 9).Value = Me.txtRebarDensity.Value
     .Cells(iRow, 10).Value = (.Cells(iRow, 9).Value / 1000) * .Cells(iRow,
8).Value

 'Calculate duration to install formwork and apply correction factor
 .Cells(iRow, 11).Value = Me.txtCarpOutput.Value

        'Apply correction factor to formwork output:

       .Cells(iRow, 12).Value = ws.Range("J20").Value +
(ws.Range("P20").Value * (Me.txtCarpOutput.Value - ws.Range("J20").Value))
       'Or=MADa+[RA2(Eo-MADa]
       'CORRECTED formwork output = Formwork MAD actual + (RA2 * (Planned
output - Formwork MAD actual)

     .Cells(iRow, 13).Value = Me.txtNoCarp.Value

        'Corrected duration to install formwork = Formwork Area / {
MADachieved formwork output * NO OF CARPS)}

        .Cells(iRow, 14).Value = (Me.txtArea.Value / ((.Cells(iRow,
12).Value * Me.txtNoCarp.Value)))
           'corrected duration =  Area of formwork / ((carp output * R [the
adjustment in output]) * no. of carpenters)

        'Formwork duration prediction [corrected duration rounded-up]
        .Cells(iRow, 15).Value = WorksheetFunction.RoundUp((.Cells(iRow,
14).Value), 0)

  'Calculate duration to install reinforcement and apply correction factor

    .Cells(iRow, 16).Value = Me.txtFixerOutput.Value
        'Apply correction factor to reinforcement output
        .Cells(iRow, 17).Value = ws.Range("k20").Value +
(ws.Range("q20").Value * (Me.txtFixerOutput.Value - ws.Range("k20").Value))

  .Cells(iRow, 18).Value = Me.txtNoFixers.Value
         'Corrected duration to install reinforcement
        .Cells(iRow, 19).Value = (.Cells(iRow, 10).Value) / ((.Cells(iRow,
17).Value) * (Me.txtNoFixers.Value))

        'Corrected reinforcment duration reounded-up
        .Cells(iRow, 20).Value = WorksheetFunction.RoundUp((.Cells(iRow,
19).Value), 0)

  .Cells(iRow, 21).Value = Me.txtSlabCycleTime()
        'Apply correction factor to slab cycle time:
        .Cells(iRow, 22).Value = ws.Range("L20").Value +
(ws.Range("r20").Value * (Me.txtSlabCycleTime().Value -
ws.Range("l20").Value))
        'Corrected slab cycle time rounded-up
        .Cells(iRow, 23).Value = WorksheetFunction.RoundUp(.Cells(iRow,
22).Value, 0)

End With
'Clear data fields:
Me.txtPourRef.Value = ""
Me.txtSSL.Value = ""
Me.txtThickness.Value = ""
Me.txtArea.Value = ""
```

```
Me.txtRebarDensity.Value = ""
Me.txtCarpOutput.Value = ""
Me.txtSlabCycleTime.Value = ""

Me.txtPourRef.SetFocus
End Sub

Private Sub Close_Window_Click()
  Unload Me

End Sub
```

Appendix G Sample Verification Calculations

Description	Calculation	Result	Difference with Database Calculation
Test 1			
Slab soffit level (m)	104m - 305mm	103.695	0
Formwork Height (m)	103.695 – 100	3.695	0
Volume of concrete (m^3)	27550*305	8402.75	0
Quantity of rebar (kg)	8402.75*172	1455.273	0
Corrected output for formwork (m^2/carp. /day)	0.73+(0.993*(10.36 - 0.73))	10.296	0
Corrected formwork duration (days)	27550 / (10.296*14)	191.128	0
Corrected output for steel fixers (kg/s.fixer/day)	137.74+(1(1.18-137.74))	1.18	0
Corrected duration to install rebar (days)	1445.273 / 1.18*7	174.973	0
Corrected Slab Cycle Time (days)	1.5+(1(12-1.5))	12	0
Test 2			
Slab soffit level (m)	8m - 275mm	7.725	0
Formwork Height (m)	7.725 - 4.7	3.025	0
Volume of concrete (m^3)	500*275	137.5	0
Quantity of rebar (kg)	137.5*155	21312.5	0
Corrected output for formwork (m^2/carp. /day)	0.73+(0.993394*(12 - 0.73))	11.926	0
Corrected formwork duration (days)	500 / (11.926*5)	8.385	0
Corrected output for steel fixers (kg/s.fixer/day)	137.74+(1(0.95-137.74))	0.95	0
Corrected duration to install rebar (days)	21.3125 / 0.95*5	4.487	0
Corrected Slab Cycle Time (days)	1.5+(1(10 - 1.5))	10	0
Test 3			
Slab soffit level (m)	44m - 300mm	43.7	0
Formwork Height (m)	43.7 - 40.5	3.2	0
Volume of concrete	450*300	135	0

(m^3)			
Quantity of rebar (kg)	135*175	23625	0
Corrected output for formwork (m^2/carp. /day)	0.73+(0.993394*(11 - 0.73))	10.932	0
Corrected formwork duration (days)	450 / (10.932*3)	13.721	0
Corrected output for steel fixers (kg/s.fixer/day)	135+(1*(1 - 135))	1	0
Corrected duration to install rebar (days)	23.625 / (1*5)	4.725	0
Corrected Slab Cycle Time (days)	1.5+(1(9 -1.5))	9	0