Exploring the Potential for the Application of Simulation Methods in Construction Project Delivery in New Zealand

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ABSTRACT

The development of simulation-based techniques used within the construction management domain is mainly to facilitate the decision-making process. These technologically-based approaches enable construction operations managers and planners to gain a better understanding of the behaviour of the real-world process under different conditions. The models resulting from simulating a construction operation, therefore, provide a basis for the support of managers and planners in making the right decisions at the right time. Simulating an operation in different scenarios gives managers and planners a clearer picture of the system behaviour in advance, rather than facing those scenarios for the first time in the real world. The more accurate the simulated models, the more feasible the achievement of controlling and managing different scenarios. Implementations of simulation approaches have become popular, and have quickly grown in number in industries other than construction. The reason attributed for the slower uptake in construction operations is the need for information technology (IT) knowledge and programming skills. However, scholars have recently strived to develop simplified programs for the construction industry to alleviate the need for IT knowledge and skills. Such programs have not yet been commercialised due to the complex nature of construction operations. To enhance the level of recognition of these programs, they should first be implemented in different types of construction operations. The development of a sound framework for their implementation would attract more attention among construction industry users (site managers and planners) and support the achievement of more accurate models.

The current research study has selected one of the most recent simplified construction simulation programs to explore its capabilities in the modelling of a particular construction operation. The selected construction operation utilised a new method of bridge construction, launching operations using a twin-truss gantry machine, in one of the largest infrastructure projects in New Zealand. The study investigated the subject matter from the perspectives of productivity improvement, and facilitation of construction operations management and planning by supporting project managers and planners with their decision-making process.

The current study design applied a case-based strategy. The design and application of the analytical pattern assisted with constructing validity and reliability throughout all phases of data collection, data composition and data analysis in the study. The data collection phase used multiple sources of evidence, including document analysis and participant observation, with best-fit distribution analysis, simulation and animation analysis undertaken in the data analysis phase.

The study found that understanding operation behaviour is a crucial part of simulating an operation. Initially, the study developed a work breakdown structure (WBS) diagram

for the gantry operation, with this translated into a specific format to fit the simulation program. Concurrent with modelling the construction process of the first bridge ramp and comparing the logic of the simulated model with the real-world project, the study developed a framework for simulating the operation. The simulation of different scenarios verified the modelling procedure embedded in the framework. Consequently, a simulated model for the launching operations was normalised by running the model on the construction of the second bridge ramp in the selected case project. The study findings indicated how the simulation program could facilitate the management of complex operations by providing managers and planners with good insights into system behaviour and by assisting them in the development of high-level schedules.

Therefore, the research demonstrates how and to what extent simulation-based approaches can achieve benefits in the improvement of construction operations productivity. The study integrates the analysis of system behaviour through using advances in technology in construction data warehousing, and emphasises the advantages of simulation approaches at the scheduling level, in scenario analysis and in identification of constraints. It is anticipated that the findings of this research could improve the current productivity rate in the New Zealand construction industry, especially as they can be used in collaboration with the principles of lean management and its particular tool: the Last Planner System (LPS).

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LIST OF ABBREVIATIONS

1stSt	time at which first instance started
Ac.	Activity
ACD	activity cycle diagram
ACM	Association for Computing Machinery
AS	activity scanning
AUTEC	Auckland University of Technology Ethics Committee
AvDur	average duration of Activities
BBNZ	Building a Better New Zealand
BCP	bridge construction project
BCSPT	Building and Construction Sector Productivity Taskforce
CAD	computer-aided design
CI	confidence interval
CIPROS	Knowledge-based Construction Integrated Project and Process Planning Simulation System
Combi	Conditional Activity
Cont	content
COOPS	Construction Object-Oriented Process Simulation System
CPM	critical path method
CSD	construction site dewatering
Cur	current amount of content at time of report
CYCLONE	CYCLic Operations NEtwork
DBH	Department of Building and Housing (NZ)
DES	discrete-event simulation
DEVS	discrete-event system specification
DISCO	Dynamic Interface for Simulation of Construction Operations
DLL	dynamic link library
DMS	decision-making support
Dur	duration
DYNASTRAT	Dynamic Strategy-based Simulation
ES	event scheduling
GC	gantry crew
GNRI	Great North Road Interchange
GPSPG	general purpose simulation program generator
GPSS	General Purpose Simulation System

GUI	graphical user interface
HSM	Hierarchical Simulation Modelling
IDE	integrated development environment
IEEE	Institute of Electrical and Electronics Engineers
INSIGHT	Interactive Simulation using Graphics Techniques
IT	information technology
km	kilometre
LP	Last Planner
LPS	Last Planner System
LstSt	time at which last instance started
MPP	massively parallel processing
MS	Microsoft
MUD	Model for Uncertainty Determination
NZ	New Zealand
OR	operations research
PDF	probability distribution function
PERT	Project Evaluation and Review Technique
PhD	Doctor of Philosophy
PI	process interaction
PMS	project master schedule
PPC	project percentage completion
PRODUF	Project Duration Forecast
Q-GERT	Queuing-Graphical Evaluation and Review Technique
RBM	resource-based modelling
RESQUE	RESource-based QUEueing (network simulation system)
SD	standard deviation (also see St.Dev.)
SD	system dynamics
SH	State Highway
SIGMA	Simulation Graphical Modeling and Analysis
SLAM	Simulation Language for Alternative Modelling
SIMAN	Simulation Management
SIMSCRIPT	FORTRAN-based Simulation Language
SimTime	simulation time (the time at which the simulation calculates the statistics report)
SMP	symmetric multi-processing
SOP	standard operating procedure
SPSPG	special purpose simulation program generator

St.Dev.	standard deviation (also see SD)
STROBOSCOPE	STate- and ResOurce-Based Simulation of COnstruction ProcEsses
Tot	total amount of resources to ever enter the Queues
Tot	total number of items started in Activities
VR	virtual reality
WBS	work breakdown structure

ATTESTATION OF AUTHORITY

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements) nor material which, to a substantial extent, has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signature Date

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CHAPTER 1

INTRODUCTION

1.0 BACKGROUND

Construction projects are complex and generally considered as the most complex undertaking in any industry (Sterman, 1992). Alvanchi (2011) highlighted that construction projects involve complex interactions among operational components, such as resources (including labour, materials and equipment). In the same vein, Fu (2013) noted that most construction operations consist of equipment-driven processes. In addition, Alvanchi (2011) proposed that the completion of a construction project requires a complex combination of dependent tasks that take place using a variety of workers with different types and levels of expertise and equipped with a range of tools with various functionalities and capabilities. The construction industry experiences great difficulty in coping with the increasing complexity of its major projects (Alvanchi, 2011). For example, complex interdependencies in a construction project’s components make it complicated to analyse. In addition, multiple interacting feedback processes included in a complex system, such as a large-scale construction project, mean that mental models and traditional cost and scheduling tools, such as the critical path method (CPM), do not adequately account for feedback effects (Peñna-Mora & Park, 2001).

Previous studies undertaken by researchers prior to 1970 identified that some quantitative methods from operations research (OR) were useful in studying construction operations. Although OR methods attempted to create a better understanding of construction processes, their application proved cumbersome and ineffective in representing real-world construction systems. In addition, it is worth noting that mathematical methods (e.g. mathematical programming, queuing theory, etc.), as investigated by AbouRizk et al. (2011), were generally too abstract to capture critical aspects of actual construction operations as performed in the field. Consequently, these studies draw our attention to the need for a method able to provide a realistic model for gaining a better understanding of construction projects.

Other researchers who have looked at the scheduling of construction projects, for example, Srisuwanrat (2009), have identified that a practical schedule in terms of time, cost and resource utilisation is essential to achieve the ultimate goal of managing construction projects. Construction project managers aim to complete a project in the least amount of time and at the lowest possible cost. Thus, as different interdependencies and relationships could occur in future project activity, it would be necessary to undertake planning in advance of this activity. According to Wu et al. (2009), advance planning is important in construction projects as it can provide certainties to benefit future states and can help to prevent adverse effects that could occur without planning.

As Martinez (1996) pointed out, it is essential that the decision-making process takes into account the complexity of construction projects. In the design of construction operations, these decisions include determining crew sizes, selecting equipment, establishing operating logic and selecting construction methods. Associated with each decision are a series of outcomes such as construction cost and time. The expected outcomes shape the decisions made. For example, a decision on the equipment fleet to use in an earth moving operation may be the one associated with the lowest expected cost (Martinez, 1996).

Tam (2007) and Ailland, Bargstädt and Hollermann (2010) attempted to draw fine distinctions between construction projects and stationary industries. Ailland et al. (2010) introduced the concept of construction processes as non-stationary with this characterised by a significant number of unforeseen events as well as by many time and cost pressures. In addition, researchers have attributed the differences between stationary and non-stationary processes to many parameters related to the requirements for technological dependencies and resource capabilities (Tam, 2007).

Similarly, Srisuwanrat (2009) highlighted the effect of construction project characteristics on the creation of a feasible project schedule that, in turn, would provide a balanced achievement of overall project objectives in terms of time, cost and quality. Contemporary literature shows that achieving project objectives in the construction project domain is a major concern. In addition, Srisuwanrat (2009) identified that using conventional planning tools imposes more difficulties. Therefore, due to these difficulties, Wu et al. (2009) undertook investigations seeking to find computer-based solutions that could improve project scheduling and speed up the whole process.

Duration is a unique feature of construction projects that Srisuwanrat (2009) has highlighted. Srisuwanrat (2009) explained that the repetition of activities included in construction projects is unique due to the differences between design, productivity of resources, availability of resources and scheduling techniques. In other words, as these factors contribute to the scheduling of activities and resources, and to defining the repetitive characteristics of activities, the duration of activities and resource use is rarely identical in each unit. Consequently, the characteristics of repetitive activities create the need for sophisticated scheduling techniques and tools to schedule projects under precedence and resource constraints (Srisuwanrat, 2009).

In bridge construction projects (BCPs), according to Chan and Lu (2012), the planning and analysis function is even more complex as these projects are associated with uncertainties arising from their construction sequence and other associated constraints, resourcing issues and structural adequacies. Ailland et al. (2010) indicated that some factors, such as shifting boundary conditions; project time and cost constraints; difficult logistics requirements; and the high probability of unexpected incidents happening, are common to non-stationary construction processes such as bridge works. Bridge works planners would therefore need to employ scheduling techniques that could provide better control and more efficiently steer the use of resources. However, individual projects that vary in type, size, function, materials and other attributes are a characteristic of the construction industry; therefore, modelling techniques would need to vary from one project to another. Ailland et al. (2010) also suggested that construction conditions change within the proposed construction processes and shift as the processes progress. As a result, planning methods are required that feature adequate adaptability and support the description of different scenarios, parallel processes, unforeseen incidents, and stochastic and fuzzy parameters (Ailland et al., 2010). One of the successful solutions applied in this context is the use of a simulation-based modelling tool. This type of tool has had intensive utilisation in support of decision-making processes (Ailland et al., 2010).

Based on the characteristics of construction processes, good opportunities could exist for the deployment of simulation techniques with the purpose of productivity improvement from the planning phase through to the erection phase. In response to the unique features of construction operations, the developed simulation model would need to be unique yet adaptable to varying circumstances (Ailland et al., 2010).

1.1 RATIONALE AND SIGNIFICANCE OF THE STUDY

The subject matter of this research aligns with two main priority areas identified by Building a Better New Zealand (BBNZ, 2011): (1) automation, industrialisation and new technology; and (2) productivity.

According to the Building and Construction Sector Productivity Taskforce report (BCSPT, 2009), productivity growth has been a particular issue in the New Zealand construction sector, necessitating new initiatives to achieve the goal of a 20% increase in productivity by 2020. Department of Building and Housing (DBH) statistics also present a disappointing picture of construction sector productivity. Therefore, the power of new technologies (such as, in this case, simulation-based approaches) needs to be investigated to see if these technologies can be applied to the construction sector to help improve its problem of low productivity.

The BBNZ (2011, pp. 21-23) strategy has proposed the following list of research topics/questions:

1. What is stopping the New Zealand construction industry from using a more efficient construction process? (p. 23)

2. Which forms of technology are delivering the envisaged benefits, in terms of cost savings, labour efficiency and quality improvements? (p. 19)

3. What emerging technologies may have application in the building and construction sector? (p. 19)

4. What are the drivers of innovation within the building and construction industry at sector, company and project level? (p. 23)

5. How can these technologies be developed for application in the building and construction sector? (p. 19)

6. What is the most effective way to spread innovation and productivity improvements throughout the building and construction industry? (p. 23)

7. What is the potential role for new and existing technologies to increase productivity? (p. 23)

8. What can we learn from overseas about these technologies? (p. 23)

9. What is the potential role for information technology in the New Zealand construction industry and how should it be introduced? (p. 23)

Therefore, in response to these research priorities, the current research explores simulation (a new technologically-based method) to improve the productivity of construction operations. The current study is essentially case study-based, and its intermediate and final outputs demonstrate how simulation could contribute to productivity improvement in the New Zealand construction industry. The potential capabilities of simulation-based tools particularly in construction processes/operations are the main focus of this study. The reason for selecting this focus was to seek opportunity points for improving construction work processes. The construction processes envisaged by the study are the typical operations that involve cyclic, repetitive sequences and uncertain characteristics. Any situation where a planner/manager needs to implement a modelling method would suit simulation exercises in which the planning and analysis of such processes could be simultaneously undertaken.

Bridge construction works are associated with uncertainties, with these possibly exacerbated by the unavailability of resources, equipment breakdown and/or the working environment (Marzouk, El-Dein, & El-Said, 2007). Inevitably, factors such as the construction sequence, resources availability and structural adequacy dictate the progress on a bridge construction project (Chan & Lu, 2012). Thus, common characteristics on bridge construction sites are the enormous time and cost pressures as well as difficult logistics requirements (Ailland et al., 2010).

Currently, only a small number of researchers have applied simulation technology to construction processes (Abbasian-Hosseini, Nikakhtar, & Ghoddousi, 2014; Wu et al., 2010), while no researchers to date have done so in the New Zealand context. Computer simulation has proven to be one of the powerful techniques for modelling uncertainties; however, its application in the construction domain is still limited (Marzouk et al., 2007). The reason generally attributed to its limited application is the difficulty of learning simulation languages and applying them to industry (Ailland et al., 2010).

For these reasons and taking into consideration the specific bridge construction method used in the case study project (the self-launching twin-truss gantry), this research intends to develop an approach that uses computer simulation, thereby transforming simulation into an accepted tool to benefit the construction industry in New Zealand by improving its productivity/performance.

1.2 RESEARCH FOCUS

The principal focus of this research is to establish the potential capabilities of simulation-based approaches in a particular construction process/operation. In undertaking the research, the view is to seek opportunity points for improving construction work processes. The construction processes envisaged by the current study are typical operations that involve a cyclic, repetitive sequence and uncertain characteristics, with a simulation model developed which supports the project planner/manager in their decision-making processes as well as their planning.

To develop the research focus in a clearer way, the following sections present the research aim, objectives and research questions.

1.2.1 RESEARCH AIM

This research aims to explore the power/capabilities of simulation techniques in construction projects. The study selected a recent construction simulation tool called STROBOSCOPE (STate- and ResOurce-Based Simulation of COnstruction ProcEsses) to investigate how its integration into traditional planning approaches which use tools such as MS Project, Primavera, etc. can benefit construction management. The major focus of the research is on construction infrastructure. The highly repetitive and complex features of these operations make them ideal for the simulation experiment. Therefore, the objectives presented in the next section were formulated to support this research with achieving its aim.

1.2.2 RESEARCH OBJECTIVES

To achieve the aim of the current research, the research objectives are as follows:

1. Review the different planning techniques to establish the potential of simulation as a suitable new planning tool for complex construction processes.

2. Identify and analyse a suitable case study project to demonstrate the potential capabilities of simulation modelling for construction processes. After securing a case study project, the next stages of the research involved preliminary scoping of the project, mapping process flows, and creating a specific work breakdown structure (WBS) and system specifications to align these project characteristics with the simulation technique/tool that was determined in (1) above.

3. Develop a simulation model for the case study project using an appropriate modelling approach. This research objective included identifying the data needed for model development and applying analytical approaches to translate the collected data into the simulation program.

4. Explore the extent to which the simulation of the studied operation could benefit the management of construction operations either through the current operation or in subsequent similar construction operations. In developing this research objective, it was envisaged that the developed model would be run to test and validate how it facilitates

the management and planning of the operation thus bringing a clear insight to the behaviour of the new system (the operations using the new method of construction) and addressing the consequences of the different constraints.

1.2.3 RESEARCH QUESTIONS

To achieve the aim and objectives of the research, the research questions developed by the study are as follows:

1- How can construction projects apply simulation modelling tools to facilitate planning and management of construction processes?

2- How can simulation methods help planners/managers to identify the consequences of different scenarios and the constraints on the project's plan before going through the real-world project?

3- How does simulation help the planner/manager to achieve a more realistic schedule when they deal with a new system? (The higher the level of the schedule to be developed, the more feasible would be the control over the constraints and their consequences.)

4- What is the link between a project's work breakdown structure (WBS) and the simulation modelling process?

1.3 RESEARCH SCOPE

To demonstrate the capabilities of simulation in scheduling linear repetitive construction projects, the case study selected was a bridge construction project. Based in Auckland, New Zealand, the project's duration coincided with the doctoral research program period (2013–2016).

The case study project involved the construction of four ramps to link a tunnel to a main highway in New Zealand. Two ramps would enter the tunnel and two others would exit the tunnel. The operations involved the delivery and installation of precast T-beams using a relatively new construction technique. This particular method used a 70-ton gantry crane in what is called 'a self-launching twin-truss gantry operation'. Chapter 6 presents further details on the case study project.

The principal challenge was to understand and process the data to derive useful information in order to improve the knowledge about the launching girder operation and its management techniques. Data were able to be collected while the process was ongoing. Therefore, the case study provided the current research with a continuous and indiscriminate stream of production data. In this way, the research was able to develop different activity cycle diagrams (ACDs) and simulation models corresponding to different real-world scenarios: this, in turn, assisted in achieving the research objectives.

1.4 RESEARCH APPROACH

The research method and strategies were progressively developed and were in line with the research questions and objectives. Considering the nature of the research problem and the different research methods, the case study strategy suited this current study the best.

According to Yin (2013), case study design should ensure that there is a clear view of what the case study is to achieve. A single embedded case design was employed in conducting this study. In line with Yin's principles, different sources of evidence were used for the data collection. The methodologies utilised in the data analysis phase included best fit distribution (probability distribution functions [PDFs]) and simulation. Moreover, the research methodologies and strategies of this study took into account the need for reliability and validity by applying the recommendations of Stuart et al. (2002) and Yin (2003). CHAPTER 5 describes the research approach in greater detail.

1.5 ORGANISATION OF THESIS

The structure of the thesis comprises nine chapters as outlined below:

Chapter 1 provides an overview of the research including the research background, rationale and significance. The chapter justifies the need for the study with brief explanations from the previous literature on the subject area. The research focus (its aim, objectives and questions) and the research approach are also presented in this chapter.

Chapter 2 presents the overview of construction operations, their features, and the management and planning of these operations. The chapter describes the difficulties encountered by construction operations managers/planners. Chapter 2 also highlights the need to understand the system behaviour so operations can be successfully managed. Consequently, the chapter concludes by addressing the potential to improve management approaches by enhancing the insight into the project process with the deployment of a new method of construction.

Chapter 3 provides a review of planning and scheduling approaches in two main categories: traditional techniques and technologically-based techniques. The chapter identifies the power and capability of simulation-based approaches to overcome the drawbacks of traditional planning methods. Focusing on the most recently developed simulation language and program, STROBOSCOPE/EZStrobe, this chapter then establishes the knowledge gap that exists in relation to exploring the capabilities of this simulation program on the modelling of a new construction method for New Zealand construction infrastructure.

Chapter 4 comprises the review of the academic literature on simulating a construction operation, and subsequently evaluates the existing simulation procedure frameworks. The chapter's emphasis is on the development of the conceptual model, and on the need to build a simulation framework for the implementation of a specific simulation program/language depending on the required features.

Chapter 5 discusses the research strategies and methodologies adopted to conduct the current research. This chapter justifies the selection of the approaches in different phases of the study: preliminary phase, data collection and data analysis. Particular attention is given to the achievement of reliability and validity in the case study design, and to the issues and limitations of the study.

Chapter 6 presents the data collection procedure and that part of the data analysis carried out in the study's preliminary phase. The chapter begins by describing the case study project and the sources of evidence available in the study's early phase. This chapter introduces the EZStrobe program. The chapter first describes the modelling procedure that began in the preliminary phase by utilising data collected on the construction of Ramp 1/Span 7, and then presents the related simulation experiments. This chapter concludes the simulation experiment by developing a final revision of the simulation model capable of presenting the real-world system behaviour in an appropriate way.

Chapter 7 presents the data collection and analysis of the construction of the rest of Ramp 1 and Ramp 4 in the studied case project. The chapter describes the building of the framework for the implementation of EZStrobe and presents the details of the framework. This chapter also presents the process of exploring the capabilities of EZStrobe by modelling different scenarios, and using different modelling functions included in the EZStrobe program. The analysis process conducted on the two different data sets enables the study to normalise the simulated model, and helps with gaining a better understanding of the system behaviour, with this described in this chapter.

Chapter 8 presents a summary of the research results. In this chapter, all significant findings are drawn together to enable the research to establish the foundation for synthesising and delivering the research objectives, with this included in the last chapter of the thesis. Chapter 8 provides a full description of the following: the framework for the implementation of EZStrobe in modelling a construction operation, the advantages of simulation at the level of scheduling, and understanding the system behaviour.

Chapter 9 concludes the thesis by integrating the key research findings in relation to the research objectives. The chapter presents the research contributions to knowledge and practice, and provides a list of recommendations for the improvement of the productivity of New Zealand construction operations. Finally, the chapter suggests opportunities for future research arising from the current study.

CHAPTER 2

CONSTRUCTION OPERATIONS MANAGEMENT

2.0 INTRODUCTION

This chapter begins by reviewing different scholars' definitions of construction operations. This review identifies and then presents some of the most important characteristics of construction operations that are responsible for making the planning and management of such operations more cumbersome. This review illustrates the need to facilitate the management of construction operations through discussing the features of construction operations as outlined in Section 2.2.

Moreover, to present the link between construction operations characteristics and their management/planning, the discussion next introduces management and planning activities in the context of construction. The review indicates that the success of management and planning is significantly dependent on an understanding of system behaviour and the construction methods applied in construction operations. The review and evaluation of the points of view expressed by researchers in previous studies continue with the discussion of decision-making activities in Section 2.4. As presented in this discussion, the influence of the characteristics of construction operations on decision-making processes highlights the need for the deployment of technologically-based approaches, such as simulation, for the successful management of construction operations. This is necessary to establish the gaps that exist with regard to new planning and management techniques and approaches, and their implementation.

2.1 CONSTRUCTION OPERATIONS

A construction project or construction operation, from the point of view of operations, can be defined in terms of processes where the term "process" means a collection of activities (Halpin & Riggs, 1992). Some other definitions proposed in previous studies highlight the interaction between components of a construction operation. For example, Cheng and Feng (2003) define construction operations as a collection of construction processes in which the flow of the processes and their resource utilisation at every step can determine the construction project's performance.

In addition, Halpin and Woodhead (1976) define construction operations as work processes that comprise physical components. According to Alvanchi (2011), the interactions between the operational components and organisational components of construction projects are complex. The complexity of construction processes ranges from simple to complicated levels. As Paulson Jr, Chan and Koo (1987) propose, complexity is the principal feature that characterises construction projects. These authors also point out another characteristic of construction projects known as the “dynamic feature” or, in other words, the feature of being dynamic. These distinctive characteristics distinguish the construction industry from other industries (Mohamed, 2002).

As explained in Chapter 1, the aim of this research is to explore the improvement opportunities from simulation modelling methods to facilitate the planning and management functions of construction activities. Owing to the strong link between the behaviour/nature of an operation and its management and planning, this section of the literature review needs to address complexity, dynamism, uniqueness, repetitiveness, continuity and uncertainty as specific features of construction operations. The following sections review and report on these features in more detail.

2.2 FEATURES OF CONSTRUCTION OPERATIONS

Martinez (1996) introduces dynamic processes as time-dependent processes which, at any given point in time, could be characterised by the states that are held within the processes. In this regard, Sterman (1992) highlights that construction operations are inherently dynamic and include multiple feedback processes. These feedback processes produce self-correcting or self-reinforcing side effects that, depending on time and resource constraints, may lead to construction operations becoming more dynamic and more complex. Peña-Mora and Park (1999) support this view by emphasising the dynamic nature of fast-tracking construction due to the existence of such dynamic feedback processes.

Sterman (2000) adds further explanation to this context. He attributes the dynamic behaviour of the system to the changes resulting from interactions among the system components (Sterman, 2000). Furthermore, J. Kim (2007) argues that construction projects have a high level of uncertainty and dynamic relationships between their operations and various resources such as labour, equipment and materials. J. Kim (2007) points out that uncertainty and randomness strongly affect a project’s duration and, consequently, very few construction projects can be completed within the estimated schedule.

A construction project encompasses several operations that need to be successfully completed for the project to achieve its objectives (Puri, 2012). Therefore, collaboration between many resources, whether machine or human, should occur to accomplish these operations (Puri, 2012). Fu (2013), in his investigation into the difficulties that surround construction project planning, emphasised project characteristics as the principal causes of these difficulties. According to Kannan (1999), each construction project is unique which means that no two construction projects are alike. Moreover, other reasons discussed as making construction project planning more cumbersome (Fu, 2013) include the complexity, dynamic nature and uncertainty of construction.

Halpin and Riggs (1992) argue that, even though each construction project is unique, their associated processes can be repetitive. The repetitive features of construction projects differentiate these projects from the repetitive nature of manufacturing as every construction project is unique and requires an enormous amount of human communication and judgement when the project is under way (Alvanchi, 2011). According to Hajjar (1999), a construction product or project is unique due to:

1- the materials, or combinations of materials, used,

2- the equipment and supplies required,

3- the engineering design and requirements, and

4- the construction method involved.

The most common example of repetitive processes is in infrastructure, highway and bridge construction operations each of which involves a complex and uncertain process including many repetitive activities (Marzouk, El-Dein, & El-Said, 2006. The different sections comprising these projects require resources to perform the same activities repetitively between each section. For example, floors make up high-rise buildings and rings make up tunnel projects. However, in these projects, the required resources should be available to fulfil similar tasks from floor to floor or from tunnel ring to tunnel ring (Marzouk et al., 2006; Srisuwanrat, 2009). Srisuwanrat (2009) called these sections “repetitive units” in which each process is repeated in every unit throughout the project. According to Srisuwanrat (2009), if any process is repeated in every unit, regardless of whether it is typical or non-typical, the process is considered repetitive. In contrast to repetitive processes, non-repetitive activities are those in which associated sub-tasks do not exist in every unit. For example, in high-rise building operations, as excavation only needs to be completed before starting the first unit, it is considered to be a non-repetitive process (Srisuwanrat, 2009). Consequently, Srisuwanrat (2009) defines projects as repetitive if they comprise a series of repetitive processes and require resources utilisation and the flow of resources between units. Units are classified, based on their design, as being either identical or similar (Srisuwanrat, 2009). The activities in each unit are usually small in number and are similar (Bakry, Moselhi, & Zayed, 2013). As Srisuwanrat (2009) explains, these activities can be typical or non-typical. The typical activity is a series of sub-activities with the same amount of work in each unit and a similar duration per repetitive unit. In contrast, a non-typical activity includes a series of sub-activities comprising different work amounts and with different durations in different units.

The advantage of unique repetitive features is the saving in time and cost due to the ability to maintain continuity in the use of different resources (Bakry et al., 2013). According to Hassanein (2003), even though maintaining resource continuity plays the role of a constraint on the planning and managing of a repetitive project, it can benefit projects in several aspects. For example, a constant workforce can be maintained by reducing the hiring and firing of labour, retaining skilled labour, maximising the use of the learning curve effect and minimising equipment idle time.

Vorster, Beliveau and Bafna (1992) classify repetitive projects into two categories: linear and non-linear. The most common examples of linear projects are the construction of highways and pipelines. In contrast, construction projects such as high-rise and multiple housing are non-linear (Hassanein & Moselhi, 2004).

Another classification of repetitive projects, according to Hsie et al. (2009), is as continuous or discrete repetitive projects. In continuous repetitive projects, the work accomplishment is not determined based on discrete work units because crews flow through the site one after the other as the project progresses. Therefore, certain amounts of distance and time intervals maintained between operations measure the work accomplishment. Conversely, discrete repetitive projects include separable work units, for example, floors in multi-storey buildings or houses in housing construction operations (Hsie et al., 2009). As Hsie et al. (2009) propose, resource utilisation plays an important role in the successful management of continuous repetitive projects. The worst scenario for resource utilisation is managing the flow of resources when they are only available in limited quantities (Hsie et al., 2009). Moreover, construction characteristics, as discussed above, can affect project scheduling and management from different perspectives.

The review of the literature in this context illustrates the extent to which the characteristics of construction operations affect managerial and planning techniques. For example, the need for efficient design is due to the resource-driven feature of construction operations (Kim, K. J., 1997), and the need for effective planning of construction projects is owing to their dynamic behaviour (Sawhney & AbouRizk, 1996). This behaviour is in response to dynamic conditions, such as unforeseen weather conditions, changes in soil conditions and the skill level of labour. Projects are subject to all of these factors, while the dynamic utilisation of resources is associated with project-level resources such as the use of a tower crane on a high-rise construction project (Sawhney & AbouRizk, 1996).

In addition, Fu (2013) emphasised unique characteristics, namely, complexity, uncertainty and dynamic nature in a study about the logistics of earth moving. Fu (2013) found that even though both strategic and tactical productivity estimations are fundamental for planning and operating, they are not easy to approach due to these characteristics. Fu (2013) also pointed out that using mathematical methods may technically seem reasonable and/or appropriate but they then become too difficult or abstract for construction practitioners.

In the same vein, Puri (2012) attempted to draw attention to the planning difficulties arising from the continuous and stochastic nature of construction activities. The author argued that planning is paramount in managing such operations. The reason is that any delay in critical activities would directly cause delay in the completion duration of the project, thus having an impact on the project's overall cost. Although the modelling of these continuous activities has been trialled through discretisation and/or combined discrete–continuous simulation, some problems continue in relation to the accuracy of the model in representing real-world scenarios (Puri, 2012).

Far fewer papers have been found in the literature (e.g. Hsie et al., 2009; Vorster et al., 1992; Lucko, 2008) arguing the viewpoint that the continuous repetitive nature of construction activities is leading to criticisms of traditional scheduling techniques such as the critical path method (CPM) and Gantt charts. As no uniform repetition of a module network occurs in continuous repetitive projects, those techniques could not accurately model the production of continuous repetitive projects.

The above discussions all provide strong evidence of the need to apply more technologically-based approaches, such as simulation, to achieve successful planning and management. Therefore, in the subsequent sections of this chapter, construction project planning and management, and decision making are introduced, with these followed by a review of management techniques and tools in the following chapter.

2.3 MANAGEMENT AND PLANNING OF CONSTRUCTION OPERATIONS

Construction management is a discipline that strives to facilitate project productivity from conception to delivery. Hajjar (1999) produces a useful list of diverse elements that are embedded in construction management. These incude:

1- feasibility studies and economic analysis,

2- budget and cash-flow planning,

3- construction contract preparation,

4- cost and schedule estimation,

5- methods planning and analysis,

6- production analysis,

7- cost and schedule monitoring and control,

8- revenue and payment management, and

9- equipment and materials management.

According to K. J. Kim (1997), the primary goals for managing construction activities include the mitigation of adverse factors and, consequently, making the work environment more predictable and manageable in terms of time, cost and quality, with completion of the project achieved with the least duration and at the lowest possible cost. Therefore, the management discipline looks toward establishing a schedule that is both “attainable” and “practical” (Srisuwanrat, 2009).

To achieve this, a deep insight into construction methods is essential (Hajjar, 1999). A clear and precise understanding of construction methods is the most important factor in construction project planning (Hajjar, 1999), with this understanding translated into the predicted duration and resource requirements during the estimating stage (Hajjar, 1999). Hajjar (1999) recommends the use of the terms “plan” or “project plan” to refer to all aspects of project planning including estimates, prediction and scheduling. In the field of construction, planning is suggested as the crucial phase in the project development cycle and is viewed as being challenging, poorly structured and knowledge-intensive (Lu, 2003).

As pointed out by Sawhney and AbouRizk (1996), effective planning needs the modelling of two specific characteristics of construction projects: dynamic conditions and the dynamic utilisation of resources.

The dynamic nature of construction projects leads to the management discipline needing to be dynamic and able to be responsive to any new changes that occur in the ongoing project. Therefore, when the project's targets are in danger, an accurate decision and management approach is essential to avoid derailing the project from its targets (Alzraiee, Zayed, & Moselhi, 2015). However, project management usually finds it challenging to balance the trade-off between the targets before and during a project (Fu, 2013).

This challenging environment calls for "the right decisions" which should be made by project management teams at strategic and tactical levels before and throughout a construction project (Fu, 2013).

2.4 DECISION-MAKING ACTIVITIES FOR CONSTRUCTION MANAGERS

Uncertainty, as one of the inherent features of construction operations, can easily lead to wrong decisions (Sobanjo, 1999). This is the reason why most research approaches that deal with process modelling in construction management strive for the support of decision-making processes (Sobanjo, 1999).

The results of previous studies, for example, the research carried out by Mawdesley, Askew and Al-Jibouri, (2004) provide evidence that decision making is subjective and strongly reliant on the planner's intuition, knowledge and experience. Furthermore, Fu (2013) explains that most construction planning decisions are made on the basis of managers' experience, judgement and rules of thumb rather than based on theory and analysis.

As discussed earlier (Section 2.2), some inherent features of construction projects make them different from other industries such as manufacturing. In addition, the discussion indicated that due to the specific characteristics of construction operations, such as being dynamic in nature, uncertainty, repetitiveness and uniqueness, decision making and, consequently, the planning/management associated with construction projects become more sophisticated than is the case in manufacturing and other industries. Halpin and Riggs (1992) attribute the poorly structured, knowledge-intensive and challenging nature of construction planning to the complicated, interactive and dynamic nature of construction projects.

In the same light, Fu (2013) concludes that construction projects are traditionally experience based, with heuristic rules the predominant techniques used in planning and management.

Fulenwider (2002) explains that construction project management involves the combination of fixed and dynamic resources, and inherent time delays for procurement, which are typically variable and difficult to predict. Therefore, the management of such processes is particularly complex.

Furthermore, Fulenwider (2002) adds that when a project starts, many changes have an impact on the initial (original) plan. Thus, a prepared schedule should serve as an effective tool, and have sufficient flexibility with which to address potential execution challenges. As a project proceeds, the schedule needs to be accurately updated in accordance with delays, and unexpected process and technical conditions. Moreover, the original plan needs logic network modifications to represent the state of ongoing work while also planning how to accomplish the rest of the work. In other words, it is essential when updating the original plan that these updates take into account the available and known information at the time of any changes (Fulenwider, 2002). When the schedule "fragnet" is inserted into the original plan and the changed events are included in the revised schedule, managers then need to decide on the consequent actions in response to these changes. As Fulenwider (2002) states, making a decision at the right time following the changed events is crucial as any delay in decision making may lead to increasing the impact of the initial event(s).

According to Fu (2013), decision making should be undertaken quickly and efficiently: in the construction industry, most of the required decisions need to be made on the job site.

Lack of time, on one hand (Fu, 2013), and dealing with a variety of organisational and operationally effective parameters which possess complex interactions, on the other hand, cause decision-making procedures to become complicated (Alvanchi, 2011).

Furthermore, different effective feedback loops formed by mutual interactions between organisationally effective factors and construction operations do not allow construction managers, when using traditional project management tools, to track or evaluate the ultimate effects of their decisions on the project's productivity and on the final cost. For these reasons, managers have become more and more dependent on their past experience and intuition during their daily decision-making activities (Alvanchi, 2011).

Over the past 20 years, both academics and industrial collaborations have studied the implementation of simulation to support managers with decision-making activities (Martinez, 1996). In the next chapter, the current study first reviewed the traditional management approaches and techniques to show how simulation-based techniques could be advantageous to construction managers. Discussions on the implementation of simulation approaches and tools in the construction domain then follow the review analysis.

2.5 SUMMARY

This chapter has presented the difficulties encountered by construction operations managers and planners due to the special features of these operations. The chapter has highlighted how an understanding of the system and construction methods could affect the approaches used in planning and managing operations in the construction domain. It became obvious from the reviewed literature that relying on personal experience cannot guarantee the successful completion of operations. Especially in this era of advanced technology in which new methods of construction are rapidly increasing, the lack of experience and knowledge presents a considerable challenge for the management of construction operations. Understanding system behaviour, predicting the constraints and their consequences, and identifying the potential execution challenges are fundamental to decision making and management. The chapter has argued that management, planning and decision making in the construction industry are cumbersome activities due to the features of the industry. Thus, it became apparent that, in construction, the potential exists for exploring the power of information technology (IT)-based approaches/techniques in facilitating these activities. Understanding the capabilities and applicability of these advanced methods could support construction planners and managers from different perspectives and, accordingly, could overcome the discussed difficulties in construction. The next chapter focuses on traditional and simulation-based planning techniques to build up a foundation from which to conduct the exploratory journey in accordance with the current research study's aim.

CHAPTER 3

CONSTRUCTION PLANNING TECHNIQUES AND APPROACHES

3.0 INTRODUCTION

This chapter presents an overview of previous research work that has evaluated planning techniques, thus providing the necessary background for the current research study. The chapter begins by introducing operations planning as a crucial step in the successful completion of a construction operation. Having presented some of the features of construction operations in the previous chapter and having noted the need for advanced planning approaches, the current chapter then continues discussions by reviewing planning techniques in two main categories: traditional and simulation-based. In Section 3.1.1, the chapter focuses mainly on the drawbacks of traditional techniques, as highlighted in previous studies. This review illustrates the need for technologically-based approaches with the most recent construction simulation approaches then introduced and reviewed in Section 3.1.2. Critical evaluation of the extant approaches led the current research to a greater focus on one simulation engine and extended program called STROBOSCOPE, with EZStrobe employed to support its objectives. In order to justify the selection of STROBOSCOPE and EZStrobe, discussions about strategies and the types of simulation tools are also included in this chapter. This review of simulation strategies and different types of simulations addresses the power of simulations in the management and planning of construction operations. Accordingly, the discussions support the current research by addressing the capabilities of simulation-based approaches in the construction domain.

3.1 CONSTRUCTION PLANNING TECHNIQUES

Construction scheduling is a tedious and time-consuming process usually carried out manually using the knowledge and experience of schedulers. For this reason, recent studies have invested a great deal of effort in seeking to resolve the problems of construction operations scheduling (Wu et al., 2009).

The planning of operations is of utmost importance as any delays in critical activities would delay the completion of projects and have a direct impact on their overall cost. Within projects, operations may complement or compete for scarce resources; thus, proper planning of these operations within the system is important to ensure timely and economical completion of the project (Puri, 2012). According to Tang et al. (2002) and Halpin and Riggs (1992), the complex, interactive and dynamic characteristics which are inherent in construction projects make planning the most crucial, knowledge-intensive, poorly structured and challenging phase in the project development cycle.

The following sections review and discuss construction planning techniques and approaches under two main categories: traditional (conventional) planning techniques and simulation-based approaches.

3.1.1 TRADITIONAL PLANNING TECHNIQUES

According to Hajjar (1999), the traditional project planning techniques used in the construction industry are not specific to this industry. These techniques, including bar charts, Gantt charts, the critical path method (CPM) and the Project Evaluation and Review Technique (PERT), are general project management techniques and have not been developed specifically for the management of complex and unique construction operations. However, these techniques have attracted much attention from the construction industry (Hajjar, 1999). Although techniques such as Gantt charts, PERT and CPM have traditionally been used by construction managers and planners, either manually or by using software packages such as Primavera and Microsoft (MS) Project (Hajjar, 1999; Wu et al., 2010), schedule overruns have been introduced as a major problem in their application (Halpin & Riggs, 1992). Furthermore, Halpin and Riggs (1992) discussed the problems with PERT estimation, pointing out that PERT underestimates project duration as it suffers from “merge event bias” which is caused by two main reasons:

1- Calculation of the early-expected finish time of a node is a summation of activity duration on the longest path leading to the node. Consequently, PERT does not take into account the potential longer path in its calculations.
2- Estimation in PERT is based on the assumption of statistical independency but this may not always be appropriate. For example, weather can create a positive correlation between activities while delay in one activity may create a negative correlation between activities.

Among these traditional management techniques, CPM and Gantt charts are the most popular with their concepts used in the development of commercial management software. However, as indicated in the literature review, not only were the developed software packages unable to assess schedule correctness, they could not optimise the schedule in accordance with total costs or total duration of the work (Wu et al., 2010).

With regard to the repetitive and resource-driven behaviour of construction projects, especially bridge construction operations, the construction industry and academia have found that CPM and other time-based methods cannot provide the appropriate techniques that are required (Srisuwanrat, 2009). In addition, as illustrated in the literature review presented in the previous chapter (Chapter 2, Section 2.2), construction operations are carried out under different conditions, for example, unfavourable weather conditions, equipment breakdown, unexpected site conditions, absenteeism of human resources, etc. However, traditional planning techniques do not account for these types of conditions (Chan & Lu, 2012; Hohmann, 1997; Ailland et al., 2010; Podolny & Muller, 1994).

As Russell and Dubey (1995) mentioned, most traditional planning techniques work well when the required resources for the completion of activities are available at the right time. Furthermore, it has been proven that many construction problems are too complex to be formulated using mathematical equations (April, Better, Glover, & Kelly 2004). The reason is that practical problems often include non-linearity, and complicated and dynamic interactions between resources and processes (Paulson Jr et al., 1987), as well as uncertainties with objectives and these constraints being cumbersome to list in mathematical equations in an effective way (Marzouk, Said, & El-Said, 2009).

As shown in the literature review, using the traditional planning/scheduling tools and techniques imposes more difficulties. However, recent studies, through the support of computer-based approaches, have strived to find solutions for improving project scheduling and speeding up the process (Srisuwanrat, 2009; Wu et al., 2009). Although both academia and the construction industry, within the last two decades, have put their efforts into developing a better technique and/or tool, most of the early approaches have been successful in resolving the problems only up to a certain degree of complexity (Srisuwanrat, 2009).

The main objectives of the development of these computer-based approaches have been to improve project scheduling and speed up the decision-making process, while capturing the complicated interactions between construction project components, feedback loops and the repetitive behaviour of construction operations. The next section therefore presents simulation approaches followed by a detailed discussion.

3.1.2 CONSTRUCTION SIMULATION TECHNIQUES

As discussed previously, traditional planning approaches have been almost limited to resolving deterministic problems rather than capturing the stochastic and repetitive nature of construction operations (Srisuwanrat, 2009). To overcome such issues, simulation has evolved as a useful model-building tool in the construction domain. The suggestion has been made that simulation could provide construction planners and managers with tools that enable them to quickly model construction operations without requiring them to possess extensive knowledge of simulation techniques (Mohamed & AbouRizk, 2005). According to Cheng and Feng (2003), the use of simulation allows planners to predict the performance of construction operations in terms of process flows and resource selection. Productivity measurement, risk and site planning are other areas in which simulation has been employed (Sawhney, AbouRizk, & Halpin, 1998). Moreover, it is claimed that computer simulation is a powerful tool for analysing both new and existing systems when the aim is to achieve improvement. According to Shannon (1992), the main purposes for the use of simulation are:

1- Evaluation of a proposed system,

2- Comparison between alternative proposals,

3- Prediction of system performance under different conditions,

4- Sensitivity analysis to determine the most significant factors affecting the performance of a system,

5- Optimisation to determine the best overall response of a system,

6- Determination of the functional relationships between a system's significant factors, and

7- Identification of the factors that cause system delays using bottleneck analysis.

The selection of the simulation modelling approaches varies depending on the nature of the projects that are to be modelled: in construction operations, these approaches are applicable to a wide spectrum of operations (Mohamed & AbouRizk, 2005). Examples are as listed in Table 3.1.

Table 3.1 Examples of developed simulations for construction operations

Operations	**Researcher**	**Simulation Tool/ Language**
Earth moving operations; tunnel operations	(Halpin, 1977; Ioannou, 1999; Martinez, 1998a; Touran & Asai, 1987)	CYCLONE (CYCLic Operations Network)
Concrete batch plants	(Lluch & Halpin, 1982)	MicroCYCLONE
Installation of precast concrete components	(Liu, 1995; Liu & Ioannou, 1992)	COOPS (Construction Object-Oriented Process Simulation System)
Earth moving operations	(Shi & AbouRizk, 1998; Hajjar, 1999)	RBM-earth Simphony
Aggregate production plants	(Hajjar & AbouRizk, 1998)	CRUISER
Construction site dewatering environment	(Hajjar & AbouRizk, 1998)	CSD (construction site dewatering)
Optimisation of construction dewatering operations	(Marzouk, 2002)	SimEarth
Location of temporary construction facilities	(Tommelein, 1999)	
Studying the impacts of changes	(Cor & Martinez, 1999; Martinez, 1996)	STROBOSCOPE

The success of simulations in construction operations has been reported by many previous studies (Abduh, Pratama, & Iskandar, 2010; Abduh, Shanti, & Pratama, 2010; AbouRizk et al., 2011; Marzouk, 2002, 2010). These studies have highlighted the effectiveness of simulation by addressing the following advantages:

1- The opportunity is always there to keep the simulation up to date during the actual operation to provide continuous feedback: this means that if the actual operation diverges from the initial simulation, potential solutions can be examined as work progresses (AbouRizk et al., 2011).

2- Simulation provides managers with an environment where they can incorporate their past knowledge or experience into random processes, such as the weather or absenteeism, drawing upon their experience and that of their companies and adapting to local conditions (AbouRizk et al., 2011).

3- Simulation is an effective tool for designing optimal resources associated with a construction operation and for analysing an ongoing operation in which the operation can be evaluated and refined in case of any changes in events (Abduh, Pratama, et al., 2010).

4- Simulation enables the user (whether the modeller or the manager) to change the logic of construction processes, by adding, deleting or updating any event. Therefore, the user can achieve suitable solutions in response to construction problems without implementing these changes in reality (El Ghandour, 2007). In the same way, Abduh, Pratama et al. (2010) propose that simulation methods allow managers to experiment with multiple scenarios in a low-cost, low-pressure environment, and allow them to identify problem areas and define possible solutions.

5- Simulation models can offer significant opportunities to model probabilistic phenomena that are often encountered in construction (AbouRizk, 2010; Halpin, 1977).

6- Some of the processes can be probabilistically modelled using simulation, such as the weather, materials delivery, work orders, etc. (AbouRizk, 2010).

7- Modern simulation languages offer significant advantages over CPM and prior simulation tools. Most languages are extensible, allowing the modeller to build sophisticated decision structures in the model to accurately represent the actual operation (AbouRizk, 2010).

8- In many cases, simulation is used simply for the reason that it allows the modeller great levels of flexibility in representing the details of resource interactions, activity relationships and various constructing logic (AbouRizk, 2010).

The focus of the current research thus became the advantages and capabilities of simulation-based techniques. The main objective developed for the research was to explore the potential for the application of one of these tools and then to examine its applicability. The literature review indicated that the power and capability of simulation are significantly influenced by the systems, languages, strategies or approaches used in the design and development of simulations (Hajjar, 1999). However, the study needed to review these strategies to identify which simulation technique would best suit the available case project. The next subsection presents different simulation strategies with different simulation tools then discussed in detail.

3.1.2.1 Different Strategies for Simulation Model Development

As mentioned by Hajjar (1999), simulation systems and approaches can be classified depending on the development strategy that has been utilised to build the simulation. Through this strategy, the concept of reusability is introduced which indicates the degree to which users are allowed to change the predefined simulation behaviour. According to this view, the reusability of simulation by users after its development is what determines its capability. The strategy of reusability, in fact, provides users with a chance to use the developed simulation for a multitude of scenarios. In accordance with this strategy, Hajjar (1999) and Ulgen, Thomasma and Mao (1989) classified simulation systems into four categories which are introduced as follows:

1- Fully documented simulation models: With fully documented simulation models, users are required to modify the simulation models by manipulating them at the same level used in their original development. This assumes that end-users are knowledgeable about the way in which the simulation system works.
2- Parameterised simulation models: Parameterised simulation models allow for model re-use by exposing a set of parameters that users can modify each time the model is simulated. The parameter values can be used to modify routing strategies, resource values and entity attributes.
3- Special purpose simulation program generators (SPSPGs): With SPSPGs, users are able to create models by selecting from a list of available domain-specific constructs and defining their parameter values as well as their relation to other elements,
4- General purpose simulation program generators: GPSPGs are integrated application development frameworks designed to allow expert users to develop, test and deploy domain-specific simulation tools for use by end-users.

As mentioned by Fu (2013), simulation should be designed on the basis of a strategy which enables the real system to be represented in an appropriate way. In continuing the literature review, the current study found another classification of simulation strategies which highlights the impact of a strategy on the way that a model is presented to a computer as well as the strategy’s impact on how the modeller views the world (Evans, J. B., 1988). Furthermore, the literature review analysis found discussions in several studies (Birtwistle et al., 1985; Hills, 1971; Hooper, 1986; Hooper & Reilly, 1982; Zeigler, Praehofer, & Kim, 1976) which struggle with the superiority of one strategy over other strategies. In contrast, another scholar, Julio Martinez (1996) considers all strategies equally general and powerful in terms of capability for the representation of a particular problem. Martinez (1996) adds that particular strategies lend themselves to more easily modelling certain classes of models. The most popular strategies utilised in the development of construction simulation, according to Abduh, Shanti et al. (2010) and Martinez and Ioannou (1999), are:

1- process interaction (PI),
2- activity scanning (AS), and
3- event scheduling (ES).

The following sections present the characteristics of these strategies.

3.1.2.1.1 Process Interaction (PI)

The process interaction (PI) strategy is recommended for developing a simulation where the system to be simulated includes flows of moving entities, and the entities have many attributes other than resources (Abduh, Shanti, et al., 2010).

According to Abduh, Shanti et al. (2010), the PI strategy is derived from the view of transactions (entities). The entities attempt to keep, acquire and release scarce resources as they move through a process (Martinez, 1996). The entities, in contrast to the machines and resources that serve them, have many attributes with this a point of differentiation. The machines and resources also have a limited number of states and little interaction with each other. However, the use of the PI strategy alone or combined with event scheduling (ES) has been recommended as the effective strategy on which to base most simulation tools and languages (e.g. GPSS, SLAM [Simulation Language for Alternative Modelling], SIMAN [Simulation Management], Q-GERT [Queuing-Graphical Evaluation and Review Technique], SIMSCRIPT [FORTRAN-based Simulation Language]) (Martinez, 1996).

Among the characteristics of construction operations as previously discussed (see Section 2.2), heavy interaction occurs between machines and resources, each of which can occupy several locations, have many attributes and be in several states (Schruben & Yücesan, 1993). Therefore, the PI strategy might not be easy to utilise in construction project simulation. However, some of the simulation languages for modelling earth moving operations (Willenbrock, 1972) and repetitive housing unit construction (Ashley, 1980) have been developed on the basis of the PI strategy.

3.1.2.1.2 Activity Scanning (AS)

As implied by the name "activity scanning (AS)", this strategy developed from the point of view of the activities that are performed and focuses on how to identify those activities and the conditions under which they take place (Abduh, Shanti, et al., 2010).

As explained by Martinez (1996), in this strategy, all flowing entities and machines are considered as resources, and the conditions for activities are constantly scanned by an AS tool to identify which activities can take place and/or be carried out.

The AS strategy is recommended for modelling operations with various activities in which the focus is on recognising the activities and the conditions required for them to take place. It has been claimed by Fu (2013) that the AS paradigm has both the capability and suitability for use in modelling construction operations. As stated by Fu (2013), construction operations include many interactions among resources in numerous states and logistical complexities are inherent to such operations; therefore, these types of operations could be more easily represented using the AS strategy (Fu, 2013). Furthermore, Martinez and Ioannou (1999) claimed that the AS strategy is the natural and most effective approach for modelling complex operations in detail.

In describing the dynamic behaviour of a system, from the viewpoint of the AS strategy, a modeller can focus on the cycles of the resident entities, for example, the busy or idle cycle of a machine. In contrast, the PI view allows a modeller to focus on the path along which transient entities flow as they pass through the system, for example, part routing in a job shop (Schruben & Yücesan, 1993).

Therefore, simulation languages based on the AS strategy, in contrast to ones based on the PI paradigm, are very strong in modelling systems that have highly independent components subject to complex activity start-up conditions. As construction operations possess this feature, the AS strategy has received more attention from construction academics and practitioners. As mentioned by Martinez (1996), all construction process simulation tools are designed and developed based on the AS paradigm and activity cycle diagrams (ACDs).

3.1.2.1.3 Event Scheduling (ES)

An event scheduling (ES) paradigm models the point of view of events that will occur or are scheduled to happen (Abduh, Shanti, et al., 2010). The ES view focuses solely on those instants in simulated time when the state of the system is modified (Schruben &

Yücesan, 1993). According to Pritsker et al. (1997), the ES strategy views the system as being constituted of a succession of unconditional events over time. When the simulation is occurring, the ES strategy can select the event with the earliest occurrence time and advance the simulation clock to that time. An example of an ES-based simulation tool is SLAM, developed by Pritsker et al. (1997).

In terms of the support provided to the modeller, the ES strategy has the lowest ranking while it has the highest ranking in terms of efficiency. The reason for the ES strategy's high level of efficiency is claimed to be that the ES-based simulation model is driven by the scheduling and execution of subroutines and events with these, in turn, scheduling the execution of other subroutines. This high level of efficiency has make the ES strategy likely to be combined with the PI and AS strategies in designing many construction simulation tools (Martinez, 1996).

3.1.2.1.4 Combination of AS, PI and ES strategies: Three-phase activity scanning (AS) method

The use of a combination of these strategies is recommended by Martinez (1996) to alleviate their weaknesses. As mentioned above, the ES strategy is usually combined with either the PI strategy or the AS strategy. The combination of ES and PI strategies can be suitable for simulating production in the manufacturing industry, whereas a more suitable combination is ES and AS strategies when modelling construction operations. Three-phase activity scanning (AS), introduced by Tocher (1963), is a modified approach that incorporates ES concepts to increase performance. The three-phase approach is claimed to be more efficient than activity scanning (AS) on its own as the simulation program does not have to scan bound (Combi [Conditional]) activities for start-up conditions. STROBOSCOPE is one example of this type of simulation language, with its development based on the three-phase activity scanning (AS) strategy. This simulation language, developed by Martinez and Ioannou (1994), has been introduced as one of the modern construction simulation languages. With regard to the powerful strategy utilised in the development of STROBOSCOPE and owing to some of its advantages as highlighted in the literature, in the current study, it was decided to conduct the exploratory research on this specific simulation language along with the new program, EZStrobe, which has been developed using the STROBOSCOPE language. Subsections 3.1.2.3 and 3.1.2.4 present more details on STROBOSCOPE and EZStrobe, respectively.

To model a three-phase activity scanning (AS)-based simulation, Halpin and Riggs (1992) suggested the use of a wheel chart or activity cycle diagram (ACD) (MacDonald & Gunn, 2012). In the same vein, Ioannou and Martinez (1999) recommended the use of an ACD as a natural means for representing the three-phase activity scanning (AS) simulation models of the main elements of the simulated process.

As discussed above, it would be possible to design different simulation tools based on the aforementioned strategies. However, in the following subsections, two main types of simulation tools introduced by Martinez and Ioannou (1999) are discussed.

3.1.2.2 Different Types of Simulation Tools

3.1.2.2.1 Process-level Simulation Tools

According to Martinez and Ioannou (1996), all construction process-level simulation tools are based on activity cycle diagrams (ACDs) and on the activity scanning (AS) simulation strategy. Consequently, they are similar at an abstract level. Even within this type of simulation system, differences occur in terms of underlying philosophy, modelling power and ease of use; however, limitations are exhibited by all of these systems with the exception of STROBOSCOPE (Martinez, 1996).

As indicated by Martinez (1996), STROBOSCOPE could easily model the issues that are very common in construction simulation. These issues include the inability to recognise differences between similar resources (i.e. the properties of resources); the inability to recognise the state of the simulated process; and the inability to make dynamic use of resource properties and the state of the simulation to define model behaviour.

3.1.2.2.2 Project-level Simulation Tools

As implied by the term "process", process-level tools represent an operation in more detail than at the project level. The smallest unit of work at the project level is generally an activity, with this able to be represented as a process or the major part of a process. MUD (Model for Uncertainty Determination), DYNASTRAT (Dynamic Strategy-based Simulation) and CIPROS (Knowledge-based Construction Integrated Project and Process Planning Simulation System) are examples of this category (Martinez, 1996), with the simulator of these systems considering the impacts of several variables on activities in terms of their daily progress. The variables include those that are calendardependent such as temperature, wind and precipitation as well as calendar-independent variables such as supervision and management (Martinez, 1996).

A review of these two categories could highlight the significant power of STROBOSCOPE and, consequently, has motivated the current study to focus more on the simulation programs, EZStrobe and ProbSched, developed using the STROBOSCOPE engine/language. By implementing the programs in Microsoft Visio, this eliminates the need for skills in IT knowledge and programming.

EZStrobe is a discrete-event system based on extended and annotated activity cycle diagrams (ACDs), while ProbSched is a graphical probabilistic schedule analysis system. EZStrobe, when compared to ProbSched, has a unique capability called “ACD Network Animation” that can animate the nodes and links of a network dynamically, as the simulation runs, and show the movement of resources and their interactions with queues and activities. In contrast, ProbSched has special capabilities in probabilistic schedule analysis, producing automatic graphical outputs to indicate the criticality of each activity and statistics reports on the activities’ duration and the overall project.

As the current study aimed to implement simulation of a bridge launching operation that uses a new method of construction, understanding the operation behaviour, including analysis of the interactions among project activities and resources, could improve the management of the operation better than analysis of the scheduling. Therefore, the study selected EZStrobe as the simulation program to provide a better chance of capturing a clear picture of the selected case project.

The next subsections present and review STROBOSCOPE and EZStrobe. Chapter 6, Section 6.2 presents further discussion about the environment of the EZStrobe program.

3.1.2.3 STROBOSCOPE

STROBOSCOPE, developed by Martinez and Ioannou (1994), is one of the modern construction simulation languages that have their origins in CYCLONE. As a general purpose simulation system, STROBOSCOPE possesses the capability of modelling a wide variety of systems with extensible features (AbouRizk et al., 2011).

STROBOSCOPE has been specifically designed and developed to model and simulate construction operations (Martinez & Ioannou, 1994). According to Palaniappan, Sawhney and Sarjoughian (2006), STROBOSCOPE uses the three-phase activity scanning (AS) approach.

The STROBOSCOPE programming language has been developed using C++ to provide a toolkit for simulating construction operations (Sawhney & AbouRizk, 1996). Furthermore, STROBOSCOPE can provide an integrated development environment (IDE) (Fulenwider, 2002) as well as graphical user interface (GUI) for common users, as STROBOSCOPE is a discrete-event simulation (DES) language based on a raw source code simulation engine (Zaheer, 2000). In other words, power users can feel comfortable with the flexibility and set of features that exist in STROBOSCOPE with the capability to extend it through completed dynamic link libraries (DLLs) under a 32-bit Windows operating system (Zaheer, 2000).

STROBOSCOPE has been classified as a process simulation tool which aims to support planning and decision making (Zaheer, 2000). It focuses substantially on forecasting the duration and managing construction to enable the process to be completed on time within the budget while meeting the required criteria, established quality requirements and other specifications (Zaheer, 2000).

As mentioned before, any process-level (process-oriented) simulation aims to present a construction operation as a collection of processes, with these processes interacting with each other through certain strategies. Moreover, according to El Ghandour (2007), the logic of operation and resource utilisation is represented through the interdependence and interlinkage of the process.

The users of STROBOSCOPE are required to write a series of programming statements which defines the network modelling elements (Fu, 2013). The STROBOSCOPE language then executes simulation-relevant algorithms to be able to access the dynamic state of the simulation and resources' attributes (Fulenwider, 2002).

As mentioned by Fu (2013), the user-friendly graphical interface of STROBOSCOPE can dynamically present the resources' attributes and the state of simulation in a construction operation. The state of simulation includes important factors, such as the number of trucks waiting for loading; the number of times an activity is performed; and the latest time at which a specific activity commences. In addition, the program provides users with modelling activities and resources in greater detail, for example, considering attributes such as the priority of an activity and the discipline of a queue (Fu, 2013).

As highlighted by AbouRizk (2010), the flexibility of the STROBOSCOPE model becomes more significant when the modeller attempts to create a practical model for use in the industry. The model developed by STROBOSCOPE includes a series of programming statements that defines a network of interconnected modelling elements. These statements, in turn, can give the elements unique behaviour and also control the simulation (Martinez, 1996).

According to Martinez (1996), the ability to dynamically access the state of the simulation and the properties of the resources involved in an operation makes STROBOSCOPE different from other construction simulations. Access to the resources' attributes is STROBOSCOPE's capability which allows operations to be sensitive to the properties of resources such as size, weight and cost on both an individual and an aggregate basis (Martinez, 1996).

Through this capability, STROBOSCOPE allows users to define attributes for modelling elements. The defined attributes can present how elements behave throughout a simulation, as they represent the duration or priority of an activity, the discipline of a queue and the amount of resource that flows from one element to another (Martinez, 1996).

STROBOSCOPE also creates the possibility of specifying most attributes with expressions. Expressions are composed of constants such as: system-maintained variables which access the state of the simulation and the properties of resources; user-defined variables; logical, arithmetic and conditional operators; and scientific, statistical and mathematical functions (Martinez, 1996).

3.1.2.3.1 STROBOSCOPE Compared to Previous Construction Simulations

STROBOSCOPE is similar to INSIGHT (Paulson Jr et al., 1987); MicroCYCLONE (Halpin, 1990); DISCO (Dynamic Interface for Simulation of Construction Operations) (Huang, Grigoriadis, & Halpin, 1994); and Simphony (Hajjar & AbouRizk, 2002), all of which aim to facilitate the preparation of the simulation engine's input data and the interpretation of its output (Wu et al., 2010).

As the final phase of any simulation modelling, interpretation of the results plays a very important role in decision making. Someone with sufficient knowledge and experience is needed to carefully read the output and trends (Zaheer, 2000).

As simulation runs can produce a large amount of output data, interpretation can become cumbersome (Zaheer, 2000). What STROBOSCOPE offers in this case is that it provides users with more flexible output reports in which users can choose only the most relevant or required results from a simulation run. The reason is that different aspects of variables, such as the average, total, standard deviation, range and criticality for any activity or for the whole project, are included in the simulation run output report. In addition, the time-series data and sensitivity analyses provided by STROBOSCOPE present its powerful capability to support decision making (Zaheer, 2000).

The results of the study carried out by Zaheer (2000) illustrate that STROBOSCOPE, in contrast to other process-oriented simulations, is able to provide sufficient trends and options for decision making with considerably fewer simulation runs. For example, the kind of approaches which can be utilised in this case when time is not a constraint and ample computing power is available include symmetric multi-processing (SMP) or massively parallel processing (MPP) machines. These approaches crash each activity day by day rather than crashing it completely. Therefore, this certainly calls for high-powered equipment as the amount of computing work required will be increased many fold (Zaheer, 2000).

Furthermore, in his study, Zaheer (2000) compared the results obtained from PERT (as a conventional method) and STROBOSCOPE simulation language. The comparison analysis illustrated that the total duration of the project that resulted from PERT was nearly the same as the average total duration that resulted from simulation. This reveals that PERT is a good approximation as long as total duration is the only criterion and multiple parallel paths of near equal duration are absent thus eliminating the chances of merge-event bias (Zaheer, 2000). In addition, these results indicate that, in most cases, simulation shows more activities as being critical than is the case with PERT.

The results of comparing STROBOSCOPE and conventional methods in the previous examples, in terms of project cost and duration, do not present significant differences. However, simulation could address additional information (e.g. standard deviation of activities, project cost and duration) which are beyond the capacity of conventional methods (Zaheer, 2000).

Furthermore, as simulation considers distribution instead of a single point estimation of activity duration, the results can be more representative (Zaheer, 2000). As indicated by Zaheer (2000), the additional information provided by simulation allows users to recognise activities which have a tendency to become critical in addition to critical activities. Other facts and observations that resulted from comparing PERT and STROBOSCOPE are in relation to planning and decision making where the simulation tool was found to provide the basis for more reliable planning from a management perspective (Zaheer, 2000).

As shown by the results of Zaheer (2000)'s study, another difference between conventional methods and simulation is the availability of the confidence interval (CI) for the collected results in simulation.

STROBOSCOPE (Martinez, 1996) and INSIGHT (Fulenwider, 2002) have proven the effectiveness of simulation approaches in dealing with the dynamic state of construction processes. The reason is that they are able to simulate construction plans prior to physical execution and, consequently, to enhance the effectiveness of planning (Martinez & Ioannou, 1996). Despite the advantages of simulation tools, in comparison to network-based methods, very few have overcome their practical limitations. In addition, their application is limited to a specific construction operation as they are not flexible enough in modelling, and also they require users to have modelling experience and knowledge (Fulenwider, 2002).

According to the definitions of "simulator" and "simulation language", what makes STROBOSCOPE different from all other tools is that STROBOSCOPE is a simulation programming language (Schruben & Yücesan, 1993). A model developed based on a simulation language has the ability to model almost any kind of system, regardless of the system's operating procedures or control logic. On the other hand, a simulator is a computer package that is able to model a system contained in a specific class of systems with little or no programming (Schruben & Yücesan, 1993).

Another advantage of STROBOSCOPE, that of storing the results generated from the site-level simulation in an MS Excel file, has been presented through the work of Fu (2013). Through this capability, the user can export MS Excel spreadsheet data into MS Project to produce a project-level schedule (in the form of bar charts and network schedules). As the construction tasks included in the STROBOSCOPE simulation are those activities included in MS Project's project-level schedule, the user can generate a higher-level schedule (such as a milestone schedule) by grouping related activities into a milestone (Fu, 2013).

Furthermore, STROBOSCOPE is able to consider uncertainty in any aspect (not only time) of the real-world system being represented (Martinez, 1996). One typical example is uncertainty in the quantities of resources produced or consumed. According to Martinez (1996), other capabilities of STROBOSCOPE's models are: dynamically selecting the resources' flow and the sequence of the operation; resource allocation to activities on the basis of complex selection schemes and the combination of resources; dynamically assigning properties to the resulting compound resources; and activating the operation subject to complex start-up conditions (not directly associated with resource availability).

It can therefore be seen that the STROBOSCOPE language possesses most of the capabilities that are desirable in general purpose simulation languages. These include multiple random number streams; sophisticated stream management; antithetic distributions; the ability to reset statistical registers or the method itself; a source-level flow control language; a statement pre-processor that allows the parameterised generation of code; and addressing selected project-level problems (Martinez, 1996).

Compared to other simulations which have specifically been designed for such problems, STROBOSCOPE acts in a different way as it is a simulation programming language and not a simulator (Martinez, 1996). For example, infinitely complex networks, such as CYCLONE, RESQUE, COOPS or CIPROS, could not model some issues but STROBOSCOPE could easily model these issues. These include: uncertainty in the amount of resources consumed and produced; processes containing operations with a non-stationary duration; processes which depend on properties of non-homogeneous sets of similar resources; and processes containing operations which are not activated unless complex resource requirements are met (Martinez, 1996).

3.1.2.3.2 Advantages of STROBOSCOPE

In addition to the advantages mentioned above (in comparing STROBOSCOPE to previous construction simulations), the following advantages have been indicated by Marzouk (2002) and Fulenwider (2002):

1- STROBOSCOPE enables users to access the state of the simulation, such as simulation time and number of entities waiting in the queues, etc., and allows users to distinguish between involved resources and entities.

2- STROBOSCOPE can recognise the uncertainties inherent in construction operations as a function of a dynamic state.

3- STROBOSCOPE can describe activity duration and sequencing in terms of the dynamic information.

4- STROBOSCOPE, as a powerful and flexible simulation language, in modelling the dynamic state of construction, can provide users with opportunities to model the underlying process-level operations.

5- STROBOSCOPE can provide various options for simulating resource utilisation processes as it can characterise and track individual resource units during simulation runs.

Following further studies, Martinez and Ioannou (1996) reported that STROBOSCOPE is able to add probabilistic functions to traditional CPM by providing the opportunity to add more functions as an add-on function to its usage.

Add-ons are dynamic link libraries (DLLs) which can be written according to the STROBOSCOPE add-on interface with conventional compiled languages: C++, C, Pascal and Fortran (Martinez, 1996). This CPM add-on allows the definition of CPM networks with stochastic durations and the calculation of various statistics about the project and its activities (Wang, W.-C. & Demsetz, 2000).

More explanation in this context was provided by Martinez and Ioannou (1996) who indicated that the probabilistic CPM add-on can formulate the duration of an activity by considering the activity's scheduling information that may be available after the activity starts. This information includes the actual start date and the duration of activities that have already started as well as the dates and floats for those activities yet to start. As mentioned before, the add-on enables the simulation to combine probabilistic scheduling with construction process simulation. Therefore, these capabilities make the CPM add-on and the STROBOSCOPE system the most powerful project planning tools available in the construction domain today (Martinez & Ioannou, 1996).

This add-on is contained in a file called "CpmAddon.dllw". The expressions for the duration of CPM activities can use the predefined variables provided by the add-on. As the CPM add-on can precede every network with a dummy START and conclude it with a dummy FINISH, the model is not required to have a single starting activity and single finishing activity which is a common CPM requirement (Martinez & Ioannou, 1996; Zaheer, 2000).

3.1.2.3.3 Examples of the Implementation of STROBOSCOPE

STROBOSCOPE has been utilised in the simulation modules of some recent discrete-event system specification (DEVS) approaches, such as Bridge-Sim (Marzouk et al., 2006). Martinez (1996) used STROBOSCOPE in that module to enable Bridge-Sim to adopt the discrete-event simulation (DES) technique. In order to activate STROBOSCOPE, MS Visual Basic 6.0 has been used in the Bridge-Sim simulation module (Martinez, 1996).

As proposed by Marzouk et al. (2006), seven construction methods, along with their respective construction techniques, are included in this module. Therefore, the simulation module can select the model that matches the construction method, with the selected model then modified to provide input data for the module. Input data include important information, such as the scope of work, number of assigned resources, number of replications, number of working hours per day and estimated durations for construction activities. When these modifications are completed, STROBOSCOPE is launched in the simulation module. STROBOSCOPE, therefore, estimates the durations which are exported to a text file in order to perform cost calculations (Marzouk et al., 2006).

In another study, STROBOSCOPE was used in a simulation model to represent five different scenarios for the planning, fabrication, shipping and installation of sheet metal ductwork in order to present how the selection of different production system designs could affect the lead time of a project (Alves, Tommelein, & Ballard, 2006).

Another example of a simulation modelling system which has been developed on the basis of STROBOSCOPE is VITASCOPE which was developed by Kamat and Martinez (2003). The aim of designing and developing VITASCOPE was to facilitate the visual simulation of the construction process in a virtual reality (VR) mode (AbouRizk et al., 2011).

In addition, STROBOSCOPE has undergone rigorous testing to verify its applicability to construction operations, for example, its employment in building an airport service centre (Martinez & Ioannou, 1994).

The literature review analysis shows that STROBOSCOPE has been used by different authors to model construction operations (e.g. Tommelein, 1998; Arbulu et al., 2002). As highlighted by Alves et al. (2006), STROBOSCOPE is also capable of being used for a number of applications in other domains.

Resources are represented in STROBOSCOPE as objects with assignable, persistent and dynamic properties. Therefore, STROBOSCOPE can actively and dynamically take into account the state of the simulated process (Martinez, 1996, p. 406). According to

Martinez (1996), general purpose simulation systems cannot easily model the multiple resource requirements and dynamic complexity of construction processes, whereas STROBOSCOPE can continuously access the state and properties of resources in the simulation model and take appropriate action.

Another example of using STROBOSCOPE as a simulation engine can be found in the work of Marzouk, El-Dein and El-Said (2007). These authors sought to develop a special purpose simulation model to assist contractors in planning a segmental bridge construction using incremental launching. In their developed model, STROBOSCOPE as a simulated engine models the activities inherent in that particular construction operation. The elements of STROBOSCOPE used to model the tasks were involved in both single form and multiple form methods.

Similarly, Said, Marzouk and El-Said (2009) used STROBOSCOPE to compare two different scenarios in the construction of bridge decks: using balanced cantilevers cast in situ and using precast cantilevers. In addition, Marzouk, Said and El-Said (2008) used STROBOSCOPE to develop a special purpose simulation model to assist with bridge decks' planning.

Other examples of using STROBOSCOPE include modelling the following: an earth moving operation (Ioannou, 1999; Martinez, 1998a); the location of temporary construction facilities (Tommelein, 1999); and the impacts of changes for highway constructions (Cor & Martinez, 1999). Furthermore, Martinez (1998a), using a STROBOSCOPE engine, developed a special simulation tool for modelling an earth moving operation with this tool called "EarthMover".

EarthMover has been categorised as a special purpose simulation tool (Martinez, 1998a). EarthMover's inputs include loading and hauling equipment and characteristics of different road segments with users able to define the inputs by dragging the corresponding elements from the available graphical interface. In addition to STROBOSCOPE (Martinez, 1996), other software has been used to build EarthMover: Visio (1997, cited in Marzouk, 2002) for graphical input entry; MS Visual Basic for non-graphical input entry; MS Excel to interpret simulation output; and Proof for animation. According to Marzouk (2002), the EarthMover drawbacks are:

1- inability to provide hourly owning and operating costs for the equipment used, with these required for calculating the total cost of an operation; and

2- inability to support users with a selection of a near optimum fleet configurations as it lacks optimisation capabilities.

In an example provided by Tommelein (1998), the use of STROBOSCOPE, with the usefulness of “lean” construction techniques, was verified in a pipe installation operation. In this example, Tommelein (1998) developed a model to analyse the impact of coordinated planning on resource management. Input variables, including production resources and duration, allowed the simulation of changes in pipe-spool buffer size, construction crew productivity and project duration (Tommelein, 1998).

In addition, STROBOSCOPE has been used to select the optimal construction method for constructing an elevated highway in Budung, Indonesia (Abduh & Ginting, 2003). The authors utilised another simulation, MicroCYCLONE, to analyse the productivity of a ready-mixed concrete batching plant.

As mentioned before, STROBOSCOPE is able to address uncertainty. Therefore, Alzraiee, Moselhi and Zayed (2015) used STROBOSCOPE to develop a planning and scheduling method to simultaneously address the uncertainty of cost and duration estimations as well as the dynamic behaviour of a project. As a result, the authors proposed a method that utilises a CPM-based network built in a DES environment and integrated with a system dynamics (SD) model.

The developed method utilises an SD model to model the policy management through capturing and quantifying its effects. This SD model builds a dynamic framework that presents the classic characteristics of the project’s dynamics. However, this dynamic framework is considered incomplete unless it is coupled with a CPM-based network that enables the job logic to be described through the sequence of activities. The CPM network can enable the model to overcome the deterministic nature of traditional methods as it uses a discrete simulation environment (Alzraiee et al., 2015).

The platform implemented in the above planning method uses ProbSched as the environment in which to develop the CPM network. According to Ioannou and Martinez (1998), ProbSched uses STROBOSCOPE as its engine. The input data for ProbSched include the duration and cost of the activity in the form of probability distributions. ProbSched uses MS Visio as its graphical user interface (GUI). Moreover, it is able to produce a graphical output to indicate the criticality and statistics of the early and late times and floats of each activity and the entire project (Ioannou & Martinez, 1998).

The work of Alzraiee et al. (2015) and Ioannou and Martinez (1998) could illustrate the potential power of the STROBOSCOPE language in the construction domain.

According to Zaheer (2000), STROBOSCOPE is a new simulation language; therefore, there is not much recognition about its capabilities nor its potential usage.

The literature review, as discussed earlier, presents good evidence of the advantages and capabilities of STROBOSCOPE. In addition, the STROBOSCOPE simulation system has been claimed as a powerful tool that can meet almost all requirements for developing complex models of any construction process (Zaheer, 2000).

Even though STROBOSCOPE can bring many benefits in terms of decision-making support (DMS) and facilitation of construction scheduling, its application is still limited to a single construction process and to the simulation of physical unit flow in resource utilisation (Peña-Mora & Park, 2001).

Due to the complexity of the construction process itself and to the effort required to prepare a model for simulation, the simulation applications developed based on process modelling like CYCLONE, STROBOSCOPE and Simphony require practitioners to model and build a representation of the operation. This means that users are still required to invest their time and effort to model the operation (Abduh, Shanti, et al., 2010).

Furthermore, as pointed out by Abduh, Shanti et al. (2010), another limitation affecting the employment of simulation in the construction industry is the availability of data for model input variables in construction projects.

3.1.2.4 EZStrobe

In 2001, in response to the need for an easy-to-learn and simple tool for analysis of construction processes, Martinez (2001) developed a new graphical simulation program called EZStrobe. As a simpler version of STROBOSCOPE, EZStrobe provides a good opportunity for practitioners with limited simulation experience to use simulation (Martinez, 2001). Even though EZStrobe was developed based on STROBOSCOPE, it excludes the possibilities of uniquely identifying resources and incorporating extremely complex logic. STROBOSCOPE and EZStrobe have been used together in many construction projects for productivity estimation and for comparing different processes. Examples of their implementation include:

1- tunnelling operations (Ioannou & Martinez, 1996),

2- “lean” construction techniques (Tommelein, 1998), and
3- asphalt paving operations (Hassan & Gruber, 2008).

As found in the literature review, EZStrobe has not yet been implemented in many construction operations. Moreover, it is hard to find studies that have used EZStrobe to model an operation and that have discussed its environment, features, model procedure, etc. in detail. This gap in the literature has prompted the current research study to explore the feasibility of implementing EZStrobe through modelling an operation using a construction method that was new in New Zealand. Furthermore, the current study decided to develop a framework for the implementation of EZStrobe in alignment with the presentation of its capabilities. In the next chapter, the literature review continues by reviewing the modelling procedure. Chapter 6 presents the EZStrobe environment and its elements, visual capability, reporting and animation.

3.2 SUMMARY

The major concern of this chapter was the critical evaluation of the capabilities of different planning techniques and approaches in construction. The drawbacks of traditional techniques prompted the study to focus on technologically-based approaches called simulation. While some studies in the literature have highlighted the power of simulation-based approaches, their implementation has not yet become salient in the construction industry. The main reasons for why construction managers and planners were reluctant to use simulation-based approaches were that these approaches needed IT knowledge and skills, and were not easy to use. With the literature review leading to a more focused discussion on the most recent construction simulation, STROBOSCOPE, in which its capabilities were highlighted, the current study identified that relatively little research has been conducted on the utilisation of the STROBOSCOPE language and EZStrobe. Through a comparison of STROBOSCOPE and previous simulation approaches, the current study identified that limited simulation studies had attempted to deploy a simulation as capable as STROBOSCOPE/EZStrobe. However, the lack of detailed research on the implementation, examination and advantages of EZStrobe has provided the current study with a knowledge gap. This led to the formulation of the research objectives and specific research questions. The current study recognised that understanding the simulation procedure in modelling an operation using EZStrobe is an essential step in a study on simulation. Therefore, the next chapter discusses and reviews the details of the modelling procedure.

CHAPTER 4

SIMULATION OF CONSTRUCTION OPERATIONS

4.0 INTRODUCTION

Having discussed the power of simulation approaches, this chapter focuses on the procedure and requirements for modelling an operation using these approaches. The first section reviews the development of a conceptual model as a foundation for simulating an operation. The literature review analysis then continues by introducing the frameworks recommended in previous studies.

The main purpose of the current chapter is to highlight the role of a conceptual model and simulation procedure framework for the achievement of accurate simulation models. The critical review of extant views in the literature identifies the extent to which the current literature has focused on the implementation of STROBOSCOPE/EZStrobe. In addition, this review identifies the potential knowledge gap that is considered in the current research.

4.1 OPERATION MODELLING PROCEDURE USING SIMULATION

A simulation project has been introduced as being a process of interpretive, developmental and analytical steps (Banks, 1998). The literature review illustrated that the procedure of modelling an operation using simulation significantly depends on the objective of the modelling, the basis of which is the following two steps:

1- developing a conceptual model, and

2- simulating an operation.

A specific framework showing the steps and their sequences to simulate an operation is hard to find. The following sections present a review of the simulation procedures and frameworks recommended in previous studies. The current study attempts to cover all the important information associated with simulation model building in this section. The literature review has shown that the different frameworks for simulation procedures contain similar steps but the steps are not in the same order. The next sections review and present, firstly, conceptual modelling and its requirements and then process modelling in construction.

4.2 CONCEPTUAL MODELLING IN SIMULATION

The notion of “conceptual modelling” is poorly defined with varying interpretations of the meaning of the term “conceptual modelling” found in the literature on simulation and modelling. For example, Robinson et al. (2011) state that conceptual modelling is not about how to implement or code a model on a computer, but is about how to decide what to include and exclude in a model. Furthermore, Zeigler et al. (1976) explain that conceptual modelling is about abstracting a model from a real or proposed system. However, another scholar, Pidd (2003), mentions that abstracting is a major issue in conceptual modelling. As the abstract should present a real-world system in an appropriate simplified model, it has been highlighted that conceptual modelling implies a sense of moving from the recognition of a problem situation which needs to be addressed by a simulated model to a determination of what is going to be modelled and how (Robinson, 2008a).

A conceptual model is introduced by Johnson (1998) in a slightly different way: a conceptual model provides a simulation-neutral view of the real world. Furthermore, Johnson (1998) suggests that simulation system-specific attributes, even if not related to the design phase, should be kept out of a conceptual model. Thus, the conceptual model should include the definitions of a simulation system and the implementation of different simulations should enable it to be realised.

Although different scholars (Arbez & Birta, 2011; Balci, 1994; Brooks, 2010; Onggo, 2010; Pace, 2000; Pidd, 2003; Robinson, 2008b; Robinson et al., 2011; Zeigler et al., 1976) define a conceptual model in different ways, all highlight the significance of conceptual modelling. For example, Onggo (2010) highlights the role of a conceptual model in building a communication link between stakeholders (simulation analysts, clients and domain experts). The fact that communication between stakeholders is important for the success of a simulation project makes the need for good conceptual model representation even more essential (Robinson & Pidd, 1998).

The literature review then highlighted that developing a conceptual model is a crucial step in simulation. The next section presents findings from the current study’s literature review on this major simulation step to illustrate the need for the development of a conceptual model in simulating any operation. The section also presents findings from the literature review related to establishing the knowledge gap.

4.2.1 REQUIREMENTS OF A CONCEPTUAL MODEL

According to Pritsker (1987), there are no measurable criteria for evaluating the worth of a conceptual model. Furthermore, as the model for developing a conceptual model is purely descriptive, it is unlikely to identify a complete set of measurable criteria at that stage (Pritsker, 1987).

The assessment criteria for conceptual modelling have been discussed by many scholars, such as Gass and Joel (1981), Ören (1981, 1984), Robinson and Pidd (1998) and Balci (2001). However, these authors have focused on the assessment criteria used in models rather than on those used in conceptual models. As illustrated by the literature review, no criteria have been formulated particularly for the assessment of conceptual models in operational research, with the exception of the list of criteria suggested by Willemain (1994). Willemain (1994), in investigating the preliminary stages of operational research interventions, found that these comprise five criteria: validity, usability, value to the clients, feasibility and aptness for the clients' problem. More generally, Brooks and Tobias (1996) identified 11 performance criteria for a good model. As explained by Robinson et al. (2011), simulation modellers and researchers involved in modelling operations have had brief discussions about the requirements of a conceptual model, including in their discussions the following four main components: validity, credibility, utility and feasibility. Table 4.1 presents the requirements for the development of a conceptual model as discussed by previous studies.

Table 4.1 Conceptual model requirements from models documented in the literature

	Pritsker (1986b)	Henriksen (1989)	Nance (1994)	Willemain (1994)	Brooks and Tobias (1996)	van der Zee and van der Vorst (2005)
Validity	Valid	Fidelity	▪ Model correctness ▪ Testability	▪ Validity ▪ Aptness for client's problem	▪ Model describes behaviour of interest ▪ Accuracy of the model's results ▪ Probability of containing errors ▪ Validity	Completeness
Credibility	Understandable	---------	---------	---------	▪ Strength of theoretical basis of model ▪ Ease of understanding	Transparency
Utility	Extensible	▪ Execution speed ▪ Ease of modification	▪ Adaptability ▪ Reusability ▪ Maintainability	▪ Value to client ▪ Usability	Portability and ease with which the model can be combined with others	----------
Feasibility	Timely	Elegance	---------	Feasibility	Time and cost to build model Time and cost to run model Time and cost to analyse results Hardware requirements	-----------

Moreover, as stated by some scholars (Robinson, 2008a; Robinson et al., 2011), very different models can be developed of the same system; therefore, it is important to identify which model would be the best one. In this vein, Carson (1986) emphasises the validity of the model, stating that a valid model in general is one which is sufficiently accurate for the purpose at hand, adding that, as there is no numeric output for the model, the notion of accuracy is of little meaning (Carson, 1986).

Robinson (2008a) adds that, even though there could be a range of conceptual models of the same system, depending on their accuracy, some might be considered as valid and credible if they are sufficiently accurate and really useful.

Hodges (1991) suggests that a "bad" model, that is, one that is not sufficiently accurate, can still be useful, believing that specific uses for such models should be identified. On this theme, Bankes (1993) continues the discussion with the idea of inaccurate models for exploratory use, while Robinson (2001) recommends the use of such models in facilitating learning about a problem situation.

Some authors (Innis & Rexstad, 1983; Ward, 1989; Salt, 1993; Chwif, Barretto, & Paul, 2000; Lucas & McGunnigle, 2003; Thomas & Charpentier, 2005) highlight that the advantages offered by simple models are more important than the conceptual model development criteria discussed above. These scholars believe that simple models can be developed faster, are more flexible, require less data, run faster and have results that are easier to interpret due to a model structure that is easier to understand.

In this vein, Ward (1989) provides clear discussions about the simplicity of models, where he makes the distinction between transparency and constructive simplicity. Ward (1989) introduces transparency as an attribute of the client (how well s/he understands the model), while constructive simplicity is an attribute of the model itself. However, transparency depends on the level of knowledge and skill of the client: this means a model that is transparent to one client may not be transparent to another client. Therefore, it is recommended that both transparency and simplicity, as well as the particular needs of the client, must be considered in developing a conceptual model (Ward, 1989).

In contrast to the importance of simplicity, as emphasised by Ward (1989), some scholars, such as Pritsker (1986b), state that the simplest model is not always the best as models need to be able to evolve as requirements change. With a similar point of view, Schruben and Yücesan (1993) propose that simpler models are not always as easy to understand, code and debug. Moreover, Davies, Roderick and Raftery (2003) emphasise that simpler models need more extensive assumptions about how a system works.

The discussions above highlight important considerations in designing a conceptual model. Indeed, whether or not a developed model is considered an appropriate model is determined by the modelling requirements used in designing the conceptual model. Therefore, the next section reviews the guidance for conceptual modelling in the construction domain to illustrate the simulation procedure in this specific industry.

4.3 PROCESS MODELLING CONCEPTS IN CONSTRUCTION

According to Halpin and Riggs (1992), the description of a construction operation is fundamental to its conceptual model development. Any modelling methodology for construction operations must have the power to meet the following requirements (Halpin & Riggs, 1992):

1- Describing an operation in which to address what is to be done and how (e.g. a technology and process focus) and who is to do it with what (e.g. resource use focus).
2- Describing in practical terms the performance of an operation which indicates the conditions under which the various processes and work tasks can be initiated, interrupted or terminated.
3- Providing the planning and management team with information related to the impact of productivity and resource use on different spreads of equipment for different crew combinations and sizes.

According to Halpin and Riggs (1992), modelling construction operations can be done at several levels, depending on whether the model's purpose is to describe, analyse or assist the user with decision making. The model can therefore be developed at the following three levels:

1- Descriptive models which require a simple modelling concept.
2- Analysis models which require the development of solution processes that operate on relevant descriptive data.
3- Decision models which need to focus on decision variables pertinent to the construction operation itself. These variables must be available to the field and office agents for manipulating the design and management of the operation.

Halpin and Riggs (1992) recommend the use of a modelling methodology which is capable of integrating a construction operation model through all of the aforementioned levels. The current study has put effort into applying Halpin and Rigg's suggestion in developing the conceptual model for this case study project. Moreover, the rationale for the modelling of construction operations, as proposed by Halpin and Riggs (1992), has been deployed in the current research study, as presented in the following sections.

4.3.1 MODELLING RATIONALE FOR CONSTRUCTION OPERATIONS

In Section 2.1, construction operations have been defined as collections of work tasks, in which the work task is a basic component of the work. The descriptions of work tasks can indicate which crew member is going to be involved in the performing of which task. Furthermore, according to the technology of the construction process and the work plan, logical dependencies exist between various tasks. The work tasks are also introduced as elemental components for the work plan, as the work plan prescribes the order in which the resources could be utilised by the operation to carry out different work tasks. In addition, the work tasks become important to construction technology, as their nature and interdependencies include the type of equipment and material used by the workforce, all of which addresses the technology deployed by a construction operation. However, an enumeration of the various resource units is required at the initial step of developing a construction operation model. Once a resource unit has been defined, a person, who is knowledgable about the construction operation, can easily identify the specific work tasks and their required resources in the operation, and accordingly determine the sequential ordering of the work tasks (Halpin & Riggs, 1992). Halpin and Riggs (1992), in agreement with Hills (1971), focus on the changes in the state of the key elements of the system (resource units) where, at any one time, resources can be considered to be either in an active state or in an idle state. In this sense, flow units can be defined as passing from state to state whenever the transfer becomes possible. Distingushing between these two states is necessary for the modelling. As the modelling and monitoring of idle and unproductive resources are crucial for measuring productivity, or lack of productivity, in a construction operation, the basic rationale for the modelling of construction operations can be summarised as:

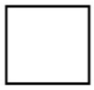
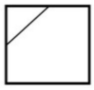
1- Identification of the individual resource units,
2- Identification of the elemental work tasks, and
3- Identification of the resource unit flow as it moves through the work tasks.

In addition to the above criteria, the requirement to model the conditions that need to be met for a work task to become active should be taken into account, as this conditional logic relates passive resources to active work tasks. In order to distinguish between unconstrained work tasks and constrained work tasks, the use of special symbols has been recommended by Halpin and Riggs (1992). These basic elements are:

1- Square node to represent the work task in an active state,
2- Circle node to represent a delay or waiting position for a resource entity which shows the resource is in an idle state, and
3- Directional flow arc to represent the path of moving a resource entity between idle and active states.

Squares and circles are the basic shapes used to model active and passive (i.e. idle) states of resource entities. They are linked together with directional arrows in the direction of the resource flow. Using these symbols in developing schematic representations of the construction operation offers a quick visual grasp of the structure of the system, with this having been used for the development of one of the most popular modelling systems in the construction domain, CYCLONE (CYCLic Operations Network). Moreover, cyclic construction processes are represented through networks of active and idle states. In this way, distinguishing between the unconstrained work task and the constrained work task, called “Normal” and “Combi”, respectively, is easier. The Combi node, which is represented as a square with a corner slash, indicates that the work task requires the initial satisfaction of conditions. The symbols required for modelling the structure and resource entity flow of construction operations are presented in Table 4.2.

Table 4.2 Basic modelling elements

Modelling element	Name of element	Description of modelling element
	NORMAL	A work task which is unconstrained in its starting logic which indicates active processing of resource entities.
	COMBI	A work task which is logically constrained in its starting logic.
	Q NODE	Q Node represents t a resource entity which queues up or waits for use of passive state resource.
	ARROW	The directional flow of the resource entity between idle and active states.

(Source: Halpin & Riggs, 1992)

In addition to the four symbols discussed above, there are two more nodes called "Counter", which has also been referred to as an "Accumulator", and "Function". The Counter node is included in the model to count the number of times a key unit passes a particular control point in the network. In other words, it helps with measuring the production as well as reflecting the level of production by scaling the single arriving unit. Furthermore, the Counter node can be used to control the number of times the system cycles before stopping or shutting down. Thus, by assigning a number of cycles to the Counter, the duration of an experiment can be controlled.

The modelling elements can be combined in several ways to model a construction operation, with the static structure of the operation providing the plan for how the operation is to be performed. The actual resources assigned to the operation traverse through this static structure. This static structure has a time-invariant nature while the movement of resources through the structure possesses a dynamic nature which indicates that performing the construction operation is time-dependent. This means that the current status of the operation and the location of the various resource enties in the static structure are functions of time, "*f(t)*" (Halpin & Riggs, 1992).

4.3.2 MODELLING PROCEDURE IN SIMULATING A CONSTRUCTION OPERATION

The main steps for modelling a given construction process, as proposed by Halpin and Riggs (1992), are outlined below:

1- Flow unit identification: in this first step, the modeller must identify the resource flow units of the system. *The selection of the flow entities is very important, as it indicates the degree of modelling detail incorporated into the operation model.*

2- Development of flow unit cycles: when the flow units, which are relevant to system performance, are identified in the next step of formulating the model, the modeller should *identify the full range of possible states that can be associated with each flow unit and develop the cycle through which each flow unit passes.*

3- Integration of flow unit cycles: performance of this step provides the elemental building componenets of the model. By integrating and synthesising the flow unit cycles, the structure and scope of the model are obtained.

4- Flow unit initialisation: the various flow units involved in the system must be initialised (both in number and initial location) in order to analyse the model and determine the system model's response.

5- Monitoring of system performance: the developed models based on the above steps may need to be modified. This can be considered as the fifth step of system design in which the determination of system productivity, flow unit characteristics and other relevant information are included as special elements of the model.

Furthermore, the literature review illustrated that the operation modelling procedure based on simulation could be completed in different ways (AbouRizk, 2010). Some studies introduce a framework which includes the development of a conceptual model as the first step (e.g. Robinson, 2012), while others start the procedure by identifying the problem, problem structuring or defining project objectives. Elsewhere, building a simulation model has been based on the completion of four phases (AbouRizk, 2010):

1. product abstraction phase (specifying the product to be built);
2. process abstraction and modelling phase (where processes, resources, the environment, etc., required to build the product are abstracted and reduced to models);
3. experimentation phase (where the simulation is carried out and experimentation occurs with the models); and
4. decision-making phase.

Moreover, the modelling phase of the study by Pidd (2003), which includes simulation of an operation, implies a different notion. This step is referred to as computer implementation and comes after a conceptual model is built in the modelling phase.

Banks (1998) and Musselman (1992) introduce a set of steps to guide model builders who use discrete-event system simulation for modelling an operation. In these frameworks (Figure 4.1 and Table 4.3), the step called “model translation” in Banks’ framework corresponds to the step called “simulating an operation and model building” in Musselman’s framework. In both frameworks, at the steps mentioned above, the constructed conceptual model is going to be coded into a computer-recognisable form (Banks, 1998).

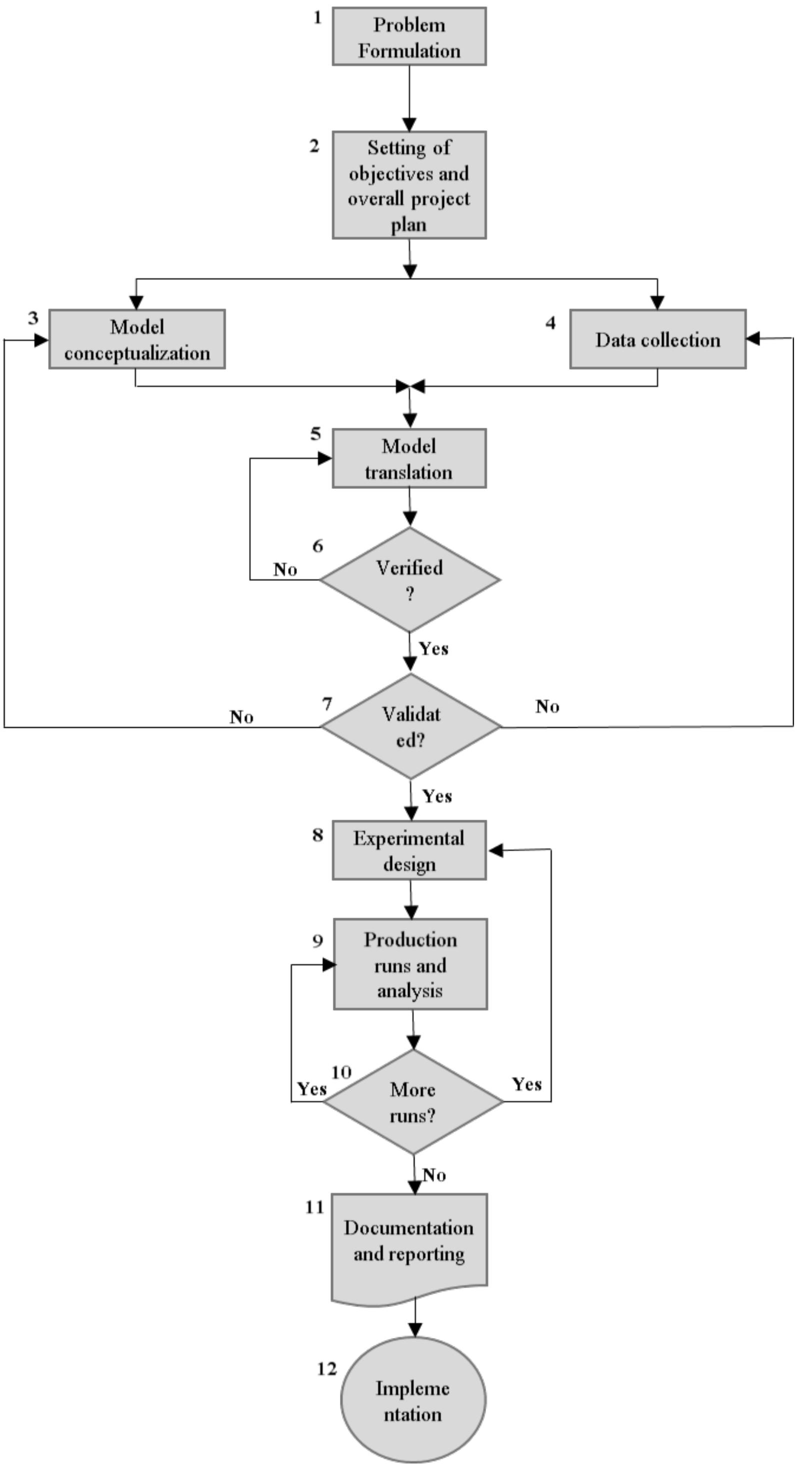


Figure 4.1 Banks' framework *(Source: Banks, 1998)*

Table 4.3 Musselman's framework

Step	Type	Description
Problem formulation	Interpretive	Define the problem to be studied, including a written statement of the problem-solving objectives
Model conceptualisation	Analytical	Abstract the system into a model described by the elements of the system, their characteristics and their interactions, all according to the problem formulation
Data collection	Developmental	Identify, specify and gather data in support of the model
Model building	Developmental	Capture the conceptualised model using the constructs of a simulation language or system
Verification and validation	Analytical	Establish that the model executes as intended and that the desired accuracy or correspondence exists between the model and the system
Analysis	Analytical	Analyse the simulation outputs to draw inferences and make recommendations for problem resolution
Documentation	Interpretive	Supply supportive or evidential information for a specific purpose
Implementation	Developmental	Fulfil the decisions resulting from the simulation

(Source: Musselman, 1998)

According to Musselman (1998), the conceptual model is referred to as the blueprint for a simulation model. According to Banks (1998) and Musselman (1998), different models can be obtained from the same blueprint as different modelling application tools can be employed.

As the current study aimed to develop a model using EZStrobe simulation for which there is no specific framework, all points recommended by Banks (1998), Musselman (1998) and Halpin and Riggs (1992) have been taken into account in conducting the simulation procedure in this study (see Section 6.3).

4.4 SUMMARY

This chapter reviewed the simulation of an operation in a general context, and then became more focused on the construction context. The literature review highlighted that conceptual model development is a foundation for each simulation procedure.

The reviews undertaken in this chapter have prepared the foundation for the steps and procedure followed in the simulation of the construction process used in the case study investigation (see Section 6.1). Thus, a conceptual model was first developed which depicts the system behaviour (the case study process) and allows for further simulation.

This chapter has argued that simulating an operation calls for a framework which presents the steps and their sequences in the simulation procedure. It is possible that the available literature has struggled with the trueness of the frameworks developed by others. As discussions within the chapter have shown, scholars have applied modifications to frameworks that were intended for use in a specific simulation, or for simulation in specific domains. No specific framework has been developed for the implementation of EZStrobe in the simulation of construction operations.

The uniqueness and complexity of construction operations, on one hand, and the deployment of a new method of construction, on the other hand, create the potential for construction operations to be explored through simulation experiments. However, the sparse research on the EZStrobe program and the newness of bridge launching operations in the studied case established the existence of some knowledge gaps within the current study's context. The study sought to pursue the following key gaps in this exploratory research:

1- The few EZStrobe experiments carried out hardly represented the modelling procedure using that particular program.

2- Absence of the WBS in the use of the twin-truss gantry machine in the New Zealand construction industry.

3- No experience in the EZStrobe program in the New Zealand construction sector to present the aspects in which such a simulation could be utilised, and the extent to which simulation could address the New Zealand construction sector's concerns.

4- A significant need to identify common constraints and the reasons for breaking premises in highly complex and repetitive operations such as bridge construction.

5- Limited knowledge of analysing the behaviour of construction operations through best fit distribution analysis.

The above knowledge gaps were then re-structured so the issues could be investigated further during the completion of the preliminary study and, subsequently, the study's main phase (Chapters 6 and 7, respectively). The next chapter presents the methodological framework and research approaches used to support the study to establish the knowledge gaps and achieve its formulated objectives.

CHAPTER 5

RESEARCH STRATEGIES AND METHODOLOGIES

5.0 INTRODUCTION

From the literature review presented in Chapters 2–4, it is evident that little research has been done to utilise STROBOSCOPE/EZStrobe simulation in the modelling of construction operations. Furthermore, the examples available in the literature show that the operation selected by the current study has the potential to become a new experience among those who have used EZStrobe. Moreover, the review of simulation approaches and modelling procedures has indicated that the purpose of the modelling and the type of simulation approach are crucial factors in the modelling procedure. The lack of research investigating a modelling framework for the implementation of STROBOSCOPE/EZStrobe presents the current study with the opportunity to address a knowledge gap in this regard. For this reason, this research aims to explore the capabilities of the aforementioned simulation (as a specific type of simulation with the capabilities claimed in the literature). In addition, the research aims to develop a framework for the implementation of this simulation in order to explore how such a simulation-based approach could help in the improvement of construction productivity (this being a major concern of the New Zealand construction industry).

The current chapter explains the development process of the research from start to completion. This chapter also presents the research design, the underlying epistemological and ontological positions, and strategies for conducting the research. Discussions then continue, providing an overview of the data collection and data analysis processes in the design of the case study, presenting information on the study's reliability and validity, and describing the limitations and the ethical issues.

5.1 PHILOSOPHICAL POSITION OF THE RESEARCH

According to Creswell (2009), the philosophical position of a research study is one of the three major elements of a research design framework. In Chua's (1986) research paradigm, the four philosophical dimensions introduced are as follows: ontology (realism vs. nominalism); epistemology (positivism vs. anti-positivism); axiology (determinism vs. voluntarism); and methodology (nomothetic vs. ideographic). The exploration of the underlying research philosophy enables the researcher to evaluate different methodologies and methods. Guba and Lincoln (1994) have recommended ontological and epistemological assumptions as the main steps in the selection of the research methodology. Ontology includes one’s view of the nature of reality, while epistemology addresses not only how the reality is known, but also the relationship between the “knower” and the “known” (Guba & Lincoln, 1994). The next sections provide further detail on these two main areas.

5.1.1 ONTOLOGY

Ontology refers to the nature of social reality (Crotty, 1998). As Wilson (2014) explained, ontology is concerned with the nature of reality which asks how we perceive the social world. In other words, ontology is about the way we think the world is (whether it is external to social actors, or that the perceptions and actions of social actors create social phenomena). In line with Burrell and Morgan (1979), Wilson (2014) suggested two main ontological possibilities: subjectivism and objectivism that are useful in selecting a research methodology. In subjectivism, there is one reality which is observable to a researcher who has little impact on the object that is being observed (Nwokah, Kiabel, & Briggs, 2009). On the other hand, objectivism is an ontological stance which implies that reality exists as the product of an individual’s mind and the engagement impacts on the observer and the situation being observed (Nwokah et al., 2009). In the same vein, Creswell (1994) mentioned that a researcher, through the ontological view, must decide whether s/he considers that the world is objective and external, or socially constructed which could be understood only by examining the perceptions of the human actors. According to Holden and Lynch (2004), objectivism and subjectivism could be described as a continuum’s polar opposites with varying philosophical positions aligned between them. These two approaches have been given various labels in the literature: for example, Easterby-Smith, Thorpe and Lowe (1991) entitled them as positivism and phenomenology, and Hughes and Sharrock (1997) introduced them as positivism and the interpretive alternative. In the social sciences, the dimensions of ontological assumptions vary from nominalism in the subjectivist approach to realism in the objectivist approach (Holden & Lynch, 2004).

In the subjectivist approach, therefore, a researcher needs to understand the subjective beliefs and attitudes that could motivate respondents to act in a particular way. In contrast, if a researcher considers the objectivist view, then s/he needs to take an external view of the world as objectivism views social phenomena based on external realities beyond our reach or control (Wilson, 2014).

While ontological assumptions are concerned with the nature of reality, epistemological assumptions are about what we accept as valid knowledge (Holden & Lynch, 2004). The next section presents the epistemological position.

5.1.2 EPISTEMOLOGY

Ontology embodies the understanding of what "it" is, while epistemology tries to understand what "it" means (Gray, 2009). Epistemology is the relationship between the knower and what the knower seeks to know (Love, Holt, & Li, 2002). This relationship can be derived from accepting the fact that knowledge can either be viewed as objectively knowable or, in contrast, only subjectively knowable (Burrell & Morgan, 1979). Therefore, on the epistemological axis, two dimensions are identified, namely, positivism and interpretivism. The positivists assume that reality is objectively given and is measurable using properties which are independent of the researcher, while interpretivists use a qualitative and subjective stance (Nwokah et al., 2009).

Construction management research deals with a blend of highly complex technical and social systems as they take place at the connection of natural science and the social sciences (Amaratunga et al., 2002). Therefore, both positivism and interpretivism have a role to play in construction management research (Amaratunga et al., 2002), with both explained in the following subsections.

5.1.2.1 The Positivist Paradigm

Positivism assumes that universal laws govern social events and that these laws enable scholars to describe, predict and control social phenomena (Kim, S., 2003). Gray (2009) defines the core arguments of positivism as follows:

1- reality consists of what is available to the senses,

2- inquiry should be based upon scientific observation, and

3- natural and human science share common logical and methodological principles, dealing with facts and not with values.

The findings of positivist studies are based on a large sample of observations and a strict scientific procedure, and have been considered the highest form of knowledge (Nonaka

& Peltokorpi, 2006). From a positivist perspective, the research takes place "behind the glass", where the researcher observes but does not interfere with a phenomenon (Kock, Gallivan, & DeLuca, 2008) and relies on quantitative methods (Howe, 2009). Opponents criticise positivism for not being capable of addressing complex social issues (Willits et al., 2011) due to its disregard of historical and contextual conditions (Orlikowski & Baroudi, 1991). In contrast to positivism, scholars drawing on interpretivist philosophies argue that knowledge and social entities cannot be understood as objective things (Nonaka & Peltokorpi, 2006).

5.1.2.2 The Interpretivist Paradigm

The interpretivist paradigm, on the other hand, seeks to understand values, beliefs and meanings of social phenomena by obtaining a deep understanding of human activities (Kim, S., 2003). Interpretivist studies accept researchers' interaction with subjects and attempt to reflect their biases as being integral to the insights derived (Kock et al., 2008). Interpretivism is realistic because facts are not considered independent of the theory or the observer (Meredith et al., 1989). Interpretivism also helps the researcher to grasp why certain characteristics or effects occur or do not occur (Meredith, 1998). The interpretivist paradigm has received increased attention in social science studies (Orlikowski & Baroudi, 1991). Researchers' assumptions, beliefs, values and interests in the interpretivist approach always intervene with their investigations: in addition, researchers are not entirely homogeneous as assumed in the positivist approach (Orlikowski & Baroudi, 1991). Therefore, these perceptions have an impact on the research process and approach. Consequently, the approach to the research is necessarily bound to the paradigmatic preferences which reduces its generalisability (Mangan, Lalwani, & Gardner, 2004).

5.1.3 ONTOLOGICAL AND EPISTEMOLOGICAL POSITION OF THE CURRENT RESEARCH

As argued by Love et al. (2002), robust methodological approaches based on both ontological and epistemological viewpoints are needed in construction management research. Therefore, construction management research could effectively resolve the problems and issues that have impacts on organisational and project performance levels.

Furthermore, referring to the paradigm continuum suggested by Morgan and Smircich (1980, p. 492) , the current study has selected research methods in accordance with the main typology of assumptions (see Table 5.1).

Table 5.1 Typology of assumptions on paradigm continuum

Source: adapted from (Morgan and Smircich, 1980, p. 492)

Positivism ←---→ Interpretivism						
	Positivist end	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Interpretivist end**
Ontological assumption	Reality as a concrete structure	Reality as a concrete process	Reality as a contextual field of information	Reality as a realm of symbolic discourse	Reality as a social construction	Reality as a projection of human imagination
Epistemological stance	To construct a positivist science	To construct systems, process, change	To map contexts	To understand patterns of symbolic discourse	To understand how social reality is created	To obtain phenomenological insight, revelation
Research methods	Experiments, surveys	Historical analysis	Interpretive contextual analysis	Symbolic analysis	Hermeneutics	Exploration of pure subjectivity

The positivist end of the continuum has been referred to as the objectivist end by Morgan and Smircich (1980). Studies assuming that the social world is the same as the physical world are located at the positivist end of this continuum. In this case, the ontological assumptions are "that reality is an external, concrete structure". Here, the researcher can use laboratory experiments and surveys as research methods. At the next stage of the continuum, reality is considered as a concrete process: moving through to the third stage, reality is derived from the transmission of information that leads to an ever-changing form and activity. In the fourth stage, "the social world is a pattern of symbolic relationships and meanings sustained through a process of human action and interaction" (Collis & Hussey, 2013, p. 49; Morgan & Smircich, 1980, p. 494).

In the next stage, individuals create the social world through language, actions and routines. At the extreme interpretivist end of the continuum which is called the subjectivist end (Morgan & Smircich, 1980), reality is regarded as a projection of the human imagination. Moreover, the interpretivist view has been introduced as a valuable approach for identifying problems in construction research studies (Seymour, Crook, & Rooke, 1997) as this approach recognises the respective viewpoints of practitioners. As

Collis and Hussey (2013) explain, the interpretivist paradigm is more acceptable in business studies. Furthermore, Cepeda and Martin (2005) add that, due to growing dissatisfaction with the quantitative-based positivistic paradigm, the interpretivist view has become more dominant.

The current research sought to evaluate the effect of the implementation of decision-making support (DMS) tools and simulation-based approaches on construction management performance and productivity. To achieve this, the study first needed to establish a conceptual framework that described the operation under investigation, namely, the gantry launching operation, as this operation had the potential for the implementation of technologically-based approaches. After establishing this level of understanding, it was then possible to identify how the tools or techniques could help construction managers to improve their managerial skills.

The interpretivist paradigm is more suitable for the current study due to the context-dependent nature of the problem and the limited knowledge among New Zealand construction organisations of the implementation of simulation-based approaches and their benefits.

Identifying the research strategy which best suits a research study, therefore, is important as it serves to establish the credibility of the work as well as supporting the study in the achievement of its objectives (Wedawatta, Ingirige, & Amaratunga, 2011).

To complete the design of the current research and to present its overall direction, Sections 5.3, 5.4 and 5.6 review and discuss the research strategies and methodologies for the collection and analysis of data.

5.2 RESEARCH STRATEGIES

According to Wedawatta et al. (2011), determining an appropriate research strategy is an important element in every research study, and is especially the case in a doctoral research study. The selection of the research strategy involves the approach taken to the entire process of the study starting from its theoretical underpinnings and going through to the selection of methodologies for data collection and data analysis. The research strategy has its focus on the problems that the research study is to investigate. However, the strategy of the research varies depending upon the problems investigated.

According to Yin (2003), applying a suitable research strategy for a particular study depends on the research questions, the control over the actual behavioural elements and the degree of focus on historical or contemporary events (Table 5.2). The second column of Table 5.2 explains the form that questions asked in a study investigation could take.

Table 5.2 Research strategies and their characteristics

Strategy	Form of question	Focus on current events	Requires control over behavioural events
Experiments	How, why	Yes	Yes
Survey	How, what, where, how many/much	Yes	No
Archival analysis	How, what, where, how many/much	Yes/No	No
History	How, why	No	No
Case study	How, why	Yes	No

(Source: Yin, 2003)

Based on Yin's (2003) criteria, various research strategies with distinctive characteristics could be selected, with these strategies having large overlaps (Saunders, Lewis, & Thornhill, 2009; Yin, 2003). However, it is important for the research study to select the most advantageous strategy. The frequently used research strategies in construction management research studies are surveys, case studies, experiments, action research and ethnography (Fellows & Liu, 2003). The following section describes these five different research strategies while Section 5.4 evaluates the most suitable strategies for the current research.

5.2.1 EXPERIMENTS

Experiments are best suited to testing theories or for theory refinement (Stuart et al., 2002). An experiment strives to discover a phenomenon away from its context so that it focuses on only a few variables. Experimental research is divided into true experiments, quasi-experiments and pre-experimental design, according to Walliman (2006).

Research in the physical and social sciences extensively uses experiments. In Meredith et al.'s (1989) study, it was shown that 70% of peer-reviewed journal articles on operational management had used experimental research. The main reason is that researchers have established the mentality that a study is of greater quality if it contains experimental design (Morrison, Ross, & Kemp, 2004). However, it seems that it would be difficult to conduct experiments if organisations, large systems or actual managers are involved in the study.

5.2.2 ACTION-BASED RESEARCH

Action-based research creates an organisational change through process studies, while other research methods study organisational phenomena without changing them at the same time (Myers, 2013). This method is widely used as it is grounded in action and aims to solve an immediate problem situation while updating theory (Coughlan & Coghlan, 2002).

The five phases in action research (Baskerville & Wood-Harper, 1996) are as follows: diagnosing, action planning, action taking, evaluating and specifying learning.

Action research is appropriate when the research questions are related to describing a series of actions that are taking place over time in a group or an organisation (Coughlan & Coghlan, 2002). It is strongly oriented towards collaboration and change involving both the researcher and the subjects. Action research is especially powerful as an instrument for researchers who are interested in finding out about the interplay between humans, technology, information and socio-cultural contexts. Action research may include all types of data collection methods but interviews and surveys are the commonly used methods (Coughlan & Coghlan, 2002). The main limitation of this strategy is the difficulty in finding resources and accessing organisations in which to conduct the research.

5.2.3 SURVEY APPROACH

Survey research is typically used to validate models or hypotheses (Kock Jr, McQueen, & Scott, 1997) and is valid in situations where direct manipulation of variables is either not feasible or unethical (DeMarrais & Lapan, 2003). Survey research is a way of collecting information from individuals (Forza, 2002), with this information then analysed using statistical techniques.

Survey research has been introduced by Pinsonneault and Kraemer (1993) as a process of collecting sample data from a larger population and making comments about the population based on the sample. According to Pinsonneault and Kraemer (1993), any survey conducted for a particular research study has three distinct characteristics. The first characteristic is the purpose of the survey, with this being to produce quantitative descriptions of some of the aspects of the studied population. The main concerns of survey analysis could be either about the relationships between variables, or about projecting findings descriptively to a predefined population (Glock & Bennett, 1967). Survey research is a quantitative method for dealing with standardised information about and/or from the study's subjects. Those subjects could be individuals, groups, organisations, communities, projects, systems or applications (Pinsonneault & Kraemer, 1993). The second characteristic is the method used for data collection in the survey research. Usually, by asking people to respond to structured and predefined questions, the required information is collected. Their answers, which may refer to themselves or to some other unit of analysis, constitute the data that should be analysed (Pinsonneault & Kraemer, 1993). The third and last characteristic is the capability of generalising the findings. Even though information is generally collected from a fraction of the population included in the study (a sample), it has to be collected in such a way as to be able to generalise the findings to the population. The sample usually needs to be large enough to allow extensive statistical analyses (Pinsonneault & Kraemer, 1993).

Furthermore, Babbie (1990) and Kerlinger (1986) explain that survey research can contribute to the advance of scientific knowledge in different ways. However, the distinctions between exploratory, confirmatory and descriptive types of survey research are important to the research being carried out through this approach (Filippini, 1997; Malhotra & Grover, 1998; Pinsonneault & Kraemer, 1993).

Filippini (1997), Malhotra and Grover (1998) and Pinsonneault and Kraemer (1993) classified survey research in accordance with the purpose of the studies into the three main categories mentioned above: exploratory, confirmatory and descriptive.

According to Gable (1994), the survey approach often offers only a "snapshot" of the situation at a certain point in time, resulting in little information on the underlying phenomena. Moreover, Gable (1994) claimed that survey research is not flexible in responding to discoveries made during data collection. Once the survey is under way, difficulties arise if a question is ambiguous, if respondents are misunderstanding a question, or if the questionnaire had omitted some crucial items. Therefore, the researcher is required to have a very good idea of the answers before starting a survey. Another major criticism of survey research is that survey researchers assume all respondents interpret questions in the same way (DeMarrais & Lapan, 2003). Moreover, some variables of interest to a researcher may not be measurable by this method. Thus, researchers should use several techniques to mitigate these limitations such as pretesting and pilot testing the questionnaires with selected groups. Due to these limitations, the current study has found the survey strategy not suitable for this research.

5.2.4 CASE STUDY RESEARCH

A case study is used in social science and management fields and is defined as "an empirical inquiry that investigates a contemporary occurrence within the real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (Yin, 2003). In research conducted under this strategy, data are collected from a few organisations through observation, questionnaire and interview. Case studies are used to present descriptions, to test theory and to develop theory from practice (Eisenhardt, 1989). As noted by Flyvbjerg (2006), case studies offer depth and richness relating to a given situation. Case study research is also apt for researching a new theory or for researching problems which are at an early stage (Cepeda & Martin, 2005).

A traditional view of case studies is that they lack rigour. In this context, Rowley (2002) states that, despite this scepticism about case study strategy, it is widely used as it can offer insights not achievable with other approaches. Some other drawbacks with case study strategy, such as lack of controllability, deductibility, repeatability and generalisability, have been addressed in the study of Lee (1989).

An often cited weakness of the case study method is the difficulty of generalising due to inherent subjectivity (Darke, Shanks, & Broadbent, 1998; Flyvbjerg, 2006; Gerring, 2006). The main reason is that case studies are based on qualitative and subjective data; that is, they can be generalised only to the particular context being studied. However, implementing some research procedures could eliminate this limitation. As suggested by Creswell and Miller (2000), extending the data gathering time on site, employing a variety of data collection methods, counter-checking with the research participants, and undertaking peer reviews and external audits are some of the ways through which the limitations of the case study method could be eliminated.

Despite the weaknesses of case study methods, many social scientists believe that this research strategy is implicitly appropriate for the exploratory phase of research, that surveys and histories are appropriate for the descriptive phase, and that experiments are the only way of pursuing explanatory or causal inquiries (Yin, 2013, p. 7)). However, the case study strategy has been considered as a preliminary method and, hence, it is thought that it cannot be used to describe or test propositions. According to Yin (2013), this hierarchical view could be questioned as most famous case studies, such as the work of Allison and Zelikow (1999), have been explanatory rather than exploratory. Moreover, in some major fields, like sociology and political science, many of the case studies have been descriptive. Moreover, distinguishing between different research strategies should not be limited by this hierarchical view (Yin, 2013).

According to Yin (2013), the case study method would be the preferred strategy when:

1- the main research questions are "how" and "why" question types,

2- the boundaries between the phenomenon and the context cannot be clearly drawn,

3- an investigator has little or no control over behavioural events, and

4- the main focus of study is a contemporary phenomenon.

Eisenhardt (1989) adds that the case study method will suit new research areas or research areas for which existing theory seems inadequate.

Benbasat, Goldstein and Mead (1987), in highlighting three strengths of the case study method, state that the case study is for learning about the state of the art and generating theories from practice. They add that the case study allows the researcher to understand the nature and complexity of the process, and that it supports the researcher in gaining valuable insight into new topics emerging in a rapidly changing field.

The case study strategy was identified as the most suitable method for the current research study, as the study aimed to explore the capabilities of simulation-based approaches to support construction project planners/managers in understanding the behaviour of a new construction system (the gantry launching operation). Accordingly, using the case study strategy, the study could address almost all of the research questions, as discussed in Section 1.2.3. Searching for site projects at the time that the current research commenced, only limited numbers of site projects were found that could serve the current study's objectives (see discussions in Section 1.2.2). The most appropriate project for the case study was found to be a case that was accessible from Auckland, the study's location, thus providing the researcher with the opportunity to carry out the fieldwork study. Therefore, the current study adopted as its research strategy a single case study.

5.2.5 ETHNOGRAPHY

Ethnography is another research strategy that has a focus on applying insights from social and cultural anthropology to the direct observations of socio-cultural phenomena (Hammersley & Atkinson, 2007). It is a qualitative research approach which is carried out in a natural setting to present the perspectives of study participants (LeCompte & Schensul, 2010). The main difference between the case study and ethnography approaches is the extent to which the researcher immerses himself or herself in the life of the social group under study (Yin, 2003). In case studies, the primary sources of data are interviews and supplementary documentary evidence, such as annual reports and minutes of meetings, while in ethnography, the data sources are supplementary data collected through participant observation. The researcher becomes a part of the community during the study and observes the behaviour and listens to participants' statements to understand what, how and why patterns occur (Hammersley & Atkinson, 2007).

Ethnographic studies provide rich information about a culture and insight into its reactions and interactions (Houser, 2013). This is mainly due to ethnography's observational nature that allows the researcher to record the behaviour and, consequently, the findings become more realistic. Generally, with ethnography, data collection takes a longer time, as do the analyses and writing up of the study outcomes. Thus, the study could become outdated (Myers, 2013). As mentioned by Fellows and Liu (2003), the results of this method could also be uncertain mainly due to the presence of the researcher. Moreover, the information collected from an ethnographic study is often very difficult to translate into tangible results (Houser, 2013). As with case studies, it is difficult to generalise the findings from ethnographic studies as the results relate to a specific setting, although problems with regard to generalisation may be overcome by conducting multiple site investigations.

5.3 STRATEGY OF THE CURRENT RESEARCH

Selection of a research strategy is an important stage in a research study as it helps the study to achieve its objectives and address the research questions. Regarding the objectives of the current study, the researcher explored the potential for the application of modelling techniques (SIS (Swarm Intelligence Symposium) Committee, 2007) in the management of construction operations. As addressed in the literature review in Chapter 3, many types of simulation-based approaches are being applied with the aim of being of benefit to construction planning and scheduling. These approaches support managers with making an appropriate decision at the right time. The current situation of the construction sector in New Zealand where the major concern, on one hand, is on improving projects' productivity and, on the other hand, the need to employ new construction methods, serves as motivation to explore how IT-based techniques can benefit the New Zealand construction industry.

Furthermore, discussions with construction managers and academics at workshops and meetings held in Auckland in the initial phase of the current study established that modern DMS tools are new in New Zealand. Although many New Zealand construction projects were seeking to gain some advantages through new technologically-based strategies, only a few could provide the study with an exploratory opportunity. Therefore, a large sample of the population was not feasible in this study. Taking into consideration the study's objectives and research questions, the case study method was found to be better suited for this research than other strategies. The next section presents and discusses the process for implementing the case study strategy in the current research.

5.3.1 DESIGNING CASE STUDY RESEARCH

When a case study has been selected as the strategy for a research study, in the next step, as in other types of research investigation, the researcher needs to design or plan how to conduct the research study (Yin, 2013).

Research design is introduced as the logic which links the data to be collected and the conclusions to be drawn to the initial questions of the study ((Rowley, 2002). Design of a case study calls for positivist and deductive approaches. This section argues for definitions of questions and propositions in advance of data collection (Rowley, 2002; Yin, 2013). Moreover, a research design could be viewed as an action plan for getting from the questions to the conclusions (Yin, 2013). However, the design of the case study should ensure that there is a clear view of what is to be achieved (Yin, 2013). In the research plan, the basic components of the research need to be defined, with these stated as follows (Rowley, 2002; Yin, 2013):

1- Research questions: Chapter 1, Section 1.2.3 discussed the formulation of the research questions for the study. These questions were generated to address the applicability of the utilisation of new planning approaches (SIS (Swarm Intelligence Symposium) Committee, 2007) in the context of the selected case.

2- Propositions of the study: This component is required for descriptive and explanatory studies (Scholz & Tietje, 2002). Some studies, in which a topic under investigation is the subject of "exploration", are based on experiments, surveys and other research methods which provide a study with a legitimate reason for not having any propositions (Yin, 2013). As the current research intended to answer the question: "how can IT-based approaches support or facilitate management of construction operations", it tried to open the door for further examination of the applicability of such approaches. Moreover, that general question led the study to explore the behaviour of a particular construction operation, namely, the gantry launching operation. The current research was found to be an exploratory type of case study; thus, its purpose, as presented in Chapter 1, would support the current study in not having study propositions at the design phase.

3- Units of analysis: The unit of analysis is another component which has been introduced as a critical factor in a case study (Rowley, 2002). The research purpose, questions, propositions and theoretical context determine the unit of analysis (Rowley, 2002). The research questions of this study (Section 1.2.3) are directed towards improving the management of operations and project productivity in construction projects, through using a case study research strategy. Therefore, the project site became central to the current research as the unit of observation and the main unit of analysis. The research was conducted by observing different sub-processes over time; therefore, this study contains multiple units of analysis. As discussed in detail in Section 6.1, these sub-processes included: launching the twin-truss gantry; preparation for delivery of super T-beams; delivery of super T-beams; placement of the intermediate super T-beam on the span; placement of the edge beam on the span; setting up the edge beam; temporary placement and permanent placement of the super T-beam; setting up the gantry directions and runway beams according to the curve of the ramp; and other processes. These sub-processes became smaller units of analysis embedded into the main unit of analysis.

4- The logic linking the data to the propositions: The fourth component is linking the data to the propositions. According to Yin (2013), this component foreshadows the data analysis steps in the case study. To design a case study, the researcher needs to be aware of the analysis techniques and their applicability, and to select the techniques which suit the case study (Yin, 2013). As a result, the case study design can create a more solid foundation for later analysis.

5- The criteria for interpreting the findings: The last component to be included in case study design is the criteria for interpreting the findings. The need for developing criteria arises when statistical analyses are included in the study. In this situation, statistical estimates serve as the criteria for interpreting the findings (Yin, 2013). As many case studies do not rely on the use of statistics (such as the current research study), the researcher needs to find other ways to develop these criteria. The main purpose of having the criteria component in the case study design is to identify and address rival explanations for the findings of the study (Yin, 2013). A detailed discussion about this component is included in the data analysis phase of the case study by Yin (2013). However, the current research presents the relevant discussion in the data analysis section (Section 5.6).

5.3.1.1 Identifying a Case Study Design: Single or Multiple, Holistic or Embedded

As shown in Table 5.3, the two dimensions into which case study designs are classified reflect the number of cases contributing to the design, and the number of units in each case. As stated by Yin (2013), the researcher needs to distinguish between single and multiple case designs prior to data collection. Single and multiple case studies are two variants of case study design which some fields, such as political science and public administration, for example, Agranoff and Radin (1991); Dion (2003); and Lijphart (1975), have tried to distinguish between. The next sections discuss these different types of case study designs.

Table 5.3 Types of case study design

	Single case designs	Multiple case designs
Holistic (single unit of analysis)	Type 1 Single/Holistic	Type 3 Multiple/Holistic
Embedded (multiple units of analysis)	Type 2 Single/Embedded	Type 4 Multiple/Embedded

5.3.1.2 Single Case Study Design

The following paragraphs present the rationale for the design of a single case study as pointed out by Yin (2013).

As stated by Yin (2013), a single case meets all required conditions for testing the theory, or for confirming, challenging or extending the theory. In addition, use of a single case can determine whether propositions of the theory are correct or whether some alternative set of explanations could be more relevant. As noted by Allison and Zelikow (1999), a single case can represent a significant contribution to the knowledge and theory building as well as helping to refocus future investigations in an entire field. According to Yin (2013), when the case is an extreme case or a unique case, this presents a second rationale for a single case design. These situations are common in clinical psychology. When a specific injury constitutes a rare case, any single case merits documentation and analysis. Another rationale, as added by Yin (2013), applies when a single case needs to be the representative or typical case: in this rationale, the objective of the single case is to capture the circumstances and conditions of an everyday or commonplace situation.

When an investigator has the opportunity to observe and analyse a phenomenon not previously accessible to social science inquiry, according to Yin (2013), this presents a further rationale for a single case design. As the single case design is revelatory in nature, the recommendation is that other investigators use a single case design when they start to deal with the same type of opportunity and are able to uncover the same phenomenon.

Furthermore, the investigator should consider that a single case study presents the vulnerability of later turning out not to be the appropriate case. Therefore, to minimise the chances of misrepresentation and to maximise the access required for collecting case study data, a careful investigation of potential cases is required. Yin (2013) suggests that *a fair warning is not to commit yourself to any single case study until all of such concerns have been covered.* Considering this point in selecting a case, the current research was limited to a case with dates for commencement and completion that matched the limited time available for undertaking the research. The current research could thus follow up two rounds of operations in the case study, and had the chance to verify model and framework development based on the second data set.

5.3.1.3 Multiple Case Study Design

With a study containing more than a single case, a multiple case design is the appropriate design. According to Herriott and Firestone (1983), the advantages and disadvantages of multiple case designs are distinctly different, with the evidence from multiple case designs considered to be more compelling. Moreover, a study can be regarded as more robust if its design is based on multiple cases. However, multiple cases are unable to meet the rationale for single case design. In comparison to single case designs, conducting multiple case designs takes more time and requires more resources. Furthermore, as the definition of single case implies, the unusual or rare case, the critical case and the revelatory case are feasible for involvement of only a single case. Therefore, it is challenging to decide to undertake multiple case studies (Yin, 2013).

As explained earlier, the aim of the current study and the situation of the construction industry in New Zealand limited the chance of involving more than one case in this study. Therefore, the design selected for the case study research was a single case. As previously mentioned, the classification of case studies can be undertaken using two dimensions. This subsection has discussed the first dimension, the one reflecting the number(s) of cases included in the research study. The next subsection presents the second dimension, the one associated with the unit of analysis.

5.3.1.4 Holistic and Embedded Case Study Design

Depending on the unit of analysis included in a case study, the case study design could be holistic or embedded (as presented in Table 5.3). The same single case may involve more than one unit of analysis, for example, when attention is given to a subunit or to subunits. When a single case study deals with units, processes or projects within a single case, then embedded single design is recommended (Scholz & Tietje, 2002; Yin, 2013), whereas holistic single design fits the study which is exploring a case in its totality. Taking into consideration the unit of analysis for the current research study, as discussed in Section 5.4.1 as well as the discussions about different case study designs, this study has selected the single embedded case design for conducting the current case-based research study.

5.3.2 RESEARCH METHODS USED TO COLLECT CASE STUDY DATA

With the research strategy chosen, the study then selected the techniques for data collection. Various data collection methods are available under the case study approach. As identified by Yin (2003), six sources of evidence are available in case studies, namely, documents, archival records, interviews, direct observation, participant observation and physical artefacts. Subsections 5.3.2.1- 5.3.2.6 briefly describe these approaches. Next, the methods used in the current study are fully described, including the rationale for their use. In addition, Yin (2003) states that the major strength of a case study data collection is the opportunity to use many different sources of evidence. To increase the quality and validity of case study research, Johnston, Leach and Liu (1999) suggest using more than one data collection method.

The following subsections present the different types of data collection methods used in research.

5.3.2.1 Document Analysis

According to Neuman and Celano (2001), documentary information is likely to be a source of evidence for every case study topic. As stated by Yin (2013), this type of information can take different forms such as:

1- letters, memoranda, email correspondence and other personal documents, such as diaries, calendars and notes;
2- agendas, announcements and minutes of meetings, and reports of events;
3- administrative documents, for example, progress reports, proposals and internal records;
4- formal studies or evaluations of the same "case" as the one being studied; and
5- news clippings and other articles appearing in the mass media or in newspapers.

The most important role of documents in case-based research is to support and enhance the reliability of the evidence gained from other sources. Documentary evidence is also called "document analysis" by Bowen (2009). In introducing this evidence source, Bowen (2009) states that it is an efficient and cost-effective method as it does not depend on the availability or participation of certain groups of people. In this vein, Yin (2013) adds that documents play an explicit role in data collection in case study research as documents are helpful in verifying the correct spelling and titles or names of organisations which might have been included in the interviews.

Yin (2013) also adds that documents can provide additional specific details to corroborate evidence from other sources. Therefore, documents can provide the chance of inferences, for example, finding a new question about communications and networking by observing the distribution list for a specific document. In this case, caution is needed as inferences should be treated as clues worthy of further investigation rather than as definitive findings, as these inferences can later turn out to be false leads.

Barzun and Graff (1985) report that over-reliance on documents as a source of evidence for case study research has been criticised. They add that this could be due to the assumption of the investigator that all kinds of documents contain unmitigated truth. Another problem with documents is in reference to the abundance of materials available through the internet (Yin, 2013). However, in both cases, the investigator is required to have a strong sense of the case study inquiry and to focus on the most relevant information. Furthermore, Bowen (2009) states that insufficient details, low reliability and biased selectivity are other limitations of this source of evidence. To avoid being misled by documentary evidence, Yin (2013) recommends sorting out the materials in accordance with the research inquiry, and then spending more time reading and/or reviewing the most pertinent information with less important materials left aside for later. Even though this procedure does not lead to the ideal situation for the use of documentary evidence, it will allow the investigator to move forward to fulfil the other case study tasks (Yin, 2013).

5.3.2.2 Participant Observation

As defined by Marshall and Rossman (2014), the term "observation" is the systematic recording of events, behaviours and artefacts in a social setting. The tools for data gathering that are under observation are natural conversations, interviews, checklists and questionnaires (DeWalt & DeWalt, 2010). Observation methods are useful to researchers in a variety of ways. As noted by Jorgensens (1989), observation methods provide researchers with opportunities to check non-verbal expressions of participants' feelings, to determine who interacts with whom, to grasp how participants communicate with each other and to check how much time is spent on various activities. As a result, observation allows detailed descriptions of natural settings and provides opportunities for viewing unscheduled events. Disadvantages identified by Waddington (2004) of the observation approach are ethical problems and participant distraction, with Jorgensens (1989) noting that limitations include access difficulties and the approach's time-consuming nature.

5.3.2.3 Archival Records

Archival records could be used in conjunction with other sources of evidence in case study research (Yin, 2013). The usefulness of this type of evidence may vary from case study to case study (Yin, 2003). According to Yin (2003), the researcher should ensure the accuracy of the information gained through archival documents. As stated by Yin (2013), the amount of this type of evidence is no indication of its accuracy as, most of the time, the archival records accessed by the investigator are in a highly quantitative format. The investigator needs to be aware that numbers alone are not sufficient signs of the accuracy of archival records as evidence. It needs to be considered that most archival records are produced for a specific purpose and a specific audience other than case study research (Yin, 2013).

5.3.2.4 Interviews

Interviews are another source of evidence in case study research mentioned by Yin (2003). Interviews provide the researcher with information from a variety of perspectives (Hays, 2004). The different kinds of interview identified in the literature are structured, semi-structured and un-structured (Fellows & Liu, 2003). The more structured the interview, the easier is the analysis. Semi-structured interviews allow participants to express their views in their own terms. Limitations of this method, as identified by Creswell (2009), are its time-consuming nature and its lack of reliability due to small sample sizes and difficulties in analysing qualitative information. A suggestion made by Yin (1994) is that the skill of the interviewer should be improved as this directly impacts on the quality of results. In a detailed guide for conducting interviews as a data collection technique, Seidman (2013) covers the stages of preparation, interview execution, recording and analysis.

5.3.2.5 Direct Observation

As a case study takes place in the natural setting of the “case”, a researcher needs to create the opportunity for direct observations (Yin, 2013). This type of observation serves as another source of evidence in case study research which assumes that the phenomena of interest have not been purely historical (Yin, 2013). In this source of evidence, the researcher can observe relevant environmental or behavioural conditions with the observation performed either casually or formally. In the case of formal observation, the investigator should develop observational instruments as part of the case study protocol. For example, people engaged in the fieldwork might be asked to assess the occurrence of certain types of behaviours during a certain time interval at the field project (Yin, 2013). Observations of meetings, footpath activities or factory work are examples of this kind of observation-based evidence. When a direct observation is made during a site visit, including occasions on which other sources of evidence, such as interviews, are being collected, the observation is performed less formally (Yin, 2013). According to Holmes (2013), direct observation is usually used when other data collection procedures, such as interviews, surveys, etc. are not effective; when the aim is to evaluate an ongoing event, situation or behaviour; or when physical outcomes are extant which can readily be seen.

It has been claimed that data collected in these observations are invaluable and useful as they provide additional information about the studied topic (Yin, 2013). This is especially the case under certain conditions, such as when the case study is about a new technology or new school curriculum. In these situations, observations aid the researcher's understanding of the actual use of the new technology or new curriculum and of any potential problems that could occur. Moreover, these observations can add new dimensions to the understanding of either the phenomenon or of the topic which is being studied (Yin, 2014). The suggestion from Yin (2014) is that having more than a single observer to make direct observations will enhance the reliability of the observational evidence.

5.3.2.6 Physical Artefacts

The last source of evidence in case study research, according to Yin (2013), is a physical or cultural artefact. This includes any physical evidence that could be collected during a site visit (Tellis, 1997). Technological devices, a tool or instrument, a work of art, notebooks, computer output and other types of physical evidence might be included in this type of evidence (Tellis, 1997). This source of evidence has less potential relevance in the most typical type of case study research (Yin, 2014). However, when relevant, these sources can be an important component in the overall case (Yin, 2014).

5.3.2.7 Summary of Data Collection Methods

According to Tellis (1997), no single source of evidence has a complete advantage over the others, with Tellis adding that these sources can be used as complementary to each other or coupled together. However, a case study should use as many sources as are relevant to the studied case. The strengths and weaknesses of these sources of evidence, as summarised by Tellis (1997, p. 21), are presented in Table 5.4.

Table 5.4 Types of sources of evidence

Source of Evidence	Strengths	Weaknesses
Documentation	1- Stable: repeated review 2- Unobtrusive: exists prior to case study 3- Exact: names, etc. 4- Broad coverage: extended time span	1- Retrievability: difficult 2- Biased selectivity 3- Reporting bias: reflects author bias 4- Access: may be locked
Archival Records	1- Same as documentation 2- Precise and quantitative	1- Same as documentation 2- Privacy might inhibit access
Interviews	1. Target: focuses on case study topic 2. Insightful: provides perceived casual inferences	1- Bias due to poor questions 2- Response bias 3- Incomplete recollection 4- Reflexivity: interviewee expresses what interviewer wants to hear
Direct Observation	1- Reality: covers events in real time 2- Contextual: covers event context	1- Time consuming 2- Selectivity: might miss facts 3- Reflexivity: observer’s presence might cause change 4- Cost: observers need time
Participant Observation	1- Same as direct observation 2- Insightful into interpersonal behaviour	1- Same as direct observation 2- Bias due to investigator’s actions
Physical Artefacts	1- Insightful into cultural features 2- Insightful into technical operations	1- Selectivity 2- Availability

(Source: Tellis, 1997, p. 21)

5.3.3 PRINCIPLES FOR DATA COLLECTION IN CASE STUDY RESEARCH

The following three principles are recommended by Yin (2014) to maximise the benefits of the use of these six sources of evidence:

1- Using multiple sources of evidence: this allows a researcher to address a broader range of historical and behavioural issues. Therefore, this principle can help with the development of converging lines of inquiry, the process of triangulation and corroboration. As a result, the case study findings can be more convincing and accurate.

2- Creating a case study database: this organises and documents the data collected for the studied case. The documentation is usually based upon two separate collections:

2-1- the data or evidentiary base, and

2-2- the report of the researcher, whether as an article, a report, a book, etc.

To practise this principle in a more efficient way, every case study project should strive to develop a presentable formal database. Unfortunately, most case studies struggle due to the lack of a formal database. Provided an investigator is aware of the need and is willing to put some effort into correcting this shortcoming of the case study (either the case has an adequate database or it does not), then s/he should find a way to build a database.

3- Maintaining a chain of evidence: this enhances the reliability of the information in a case study. This principle allows an external observer, for example, the reader of the case study, to follow the derivation of any evidence from initial research questions through to the conclusion of the case study. The external observer should be able to trace five steps: case study report; case study database; citations to specific evidentiary sources in the case study database; case study protocol; and case study questions. The tracing should be possible in either direction, from conclusions back to the initial research questions or from questions forward to conclusions. No original evidence should be lost due to carelessness or bias. Otherwise, the researcher will fail to receive the appropriate attention in considering the facts of the case.

5.4 DATA COLLECTION METHODOLOGIES FOR THE CURRENT STUDY

Data collection is a vital phase of research (Yin, 2013). In line with the principles presented above, the current study planned to collect data from multiple sources of evidence including participant observations and documentation. Through a preliminary study, a database was then developed so the studied case could understand the types of information that needed to be collected (see Table 6.7, Figure 5.1-Figure 5.3).

The initial method chosen for data collection was observation, with this used to explore the behaviour of the studied construction operation (to explore the system behaviour, identifying incidents and uncertainties, developing the work breakdown structure [WBS] and tracking the sequence of performances). The researcher acted as an observer (i.e. not an employee of the construction organisation) with the only interest being in generating a more complete understanding of the behaviour of the case study. Informal conversations and interactions with the gantry operation's crew, planner team and supervisors were also important components at this step.

Through participant observation, the researcher aimed to gain more details about the sequence of performances; interactions between resources; causes of incidents; impact of incidents and uncertainties on project progress; changing the method of construction; and making an urgent decision in the event of an accident. The researcher observed two processes, comprising the construction of Ramp 1 and Ramp 4 (see Section 6.1 for details of the case study project). For each process studied, the researcher observed all the process steps and recorded the list of activities, their sequences, required resources and duration to their completion. The template presented in Figure 5.1 was the basis used to collect the detailed information. This template was designed as a database (in line with the second principle, as discussed above), and was modified a few times to provide the current research with a more appropriate database. Consequently, this helped the study to maintain the chain of evidence according to the third principle of Yin (2014). Different versions of the aforementioned database are presented in Tables 5.5–5.11.

Table 5.5 First draft of database for recording information on gantry operation

Operation hours					Duration	Net Duration	Notes/ Reasons for non-completion
start	Smoko		Total Break (including meeting, incident, drug test etc)	Finish			
7.50			1	16.33	8.83	7.83	
7.50	10-10.30	15.00-15.30	1	19	11.50	10.50	
7.25	10-10.50	14.00-14.30	1.2	17	9.75	8.55	
Weekend							
7.00	10.30-11.00	14.30-15.00	1	17	10.00	9.00	
7.00			1	17	10.00	9.00	
7.50			1	17.75	10.25	9.25	
7.50			1	16.16	8.66	7.66	
7.50			1	17	9.50	8.50	
7.00				20.00	13.00	13.00	
7.00	09.15-10.00		0.45	16.25	9.25	8.80	
7.00			1	17.00	10.00	9.00	
7.00	15.30-16.20		0.5	18.33	11.33	10.83	
7			1	13	6.00	5.00	
Weekend							
19.5	00.20-01.00		0.4	3.50	8.00	7.60	
19.5	23.00-23.40		0.4	4.00	8.50	8.10	
19.5	00.00-00.30		0.4	4.16	8.66	8.26	
19	01.35-02.30		1	4.00	9.00	8.00	
19.5	12.50-02.30 (Including Meeting)		3.25	4.33	8.83	5.58	drug test

The first draft was developed and utilised for two weeks; however, it became clear that more details needed to be recorded.

The main purposes for observing the gantry launching operation process were:

1- exploring the system behaviour by recording data based on field note taking and conducting participant observation on site,

2- developing the WBS,

3- identifying opportunities for the implementation of simulation,

4- identifying the power of simulation in modelling the operation,

5- identifying opportunities for decision-making support (DMS) using simulation, and

6- identifying how simulation-based techniques could enhance the level of perception of the system and, consequently, improve management and productivity.

To collect the above information, the researcher developed a new template (presented in Tables 5.6–5.9). Using this template enabled the researcher to take notes, to record many details required later for the simulation process and, at any time, to recall additional information related to the behaviour of operations. The planner team, site engineers and gantry crew (also called “database users” in this section) expressed concerns about the database used to record their data. Therefore, in each development step, the researcher sent revised versions of the database template to these work crews with their feedback requested. Even though the latest revision of the template was advantageous for the current research, from a practical view, it was not user-friendly for the organisation’s users. In response to their feedback, two new versions of the template were developed. The first version was in the format of an MS Excel spreadsheet: the following version was in a simple tabulating format that allowed users to record and share electronically through emails or the organisation’s internal network (ORBIT).

Table 5.6 Preliminary observations of work process: Field Note 1

date	Operation hours					Duration	Net Duration	additional work because of limited number of resources such as erection supports	Information on beam has been delivered to the site	
	start	Smoko		Total Break (including meeting, incident, drug test etc)	Finish				beam number/ arrival time/	beam number/ arrival time/
2014.02.11									37/ ?	
2014.02.12	7.30			1	16.2	8.90			35/09.15	
										39/14.00
2014.02.13	7.30	10-10.30	15.00-15.30	1	19	11.70				

Table 5.7 Preliminary observations of work process: Field Note 2

extra works on delivered beam included preparation of beam such as edge form and timbering , etc. untill being ready to be placed on the ground	information on lifting up the beam to the gantry crane and moving gantry forward to the span	shift siding the gantry
delivering the beam 35 starts at 9.15 and preparation finished at 10.00		
extra works on Beam no. 39 :14.00-16.20		
preparation of beam no.39 to be erected to the gantry started at 07.30-10.55	beam no.39 : lifting up from 10.55-10.58, moving forward from 10.58-11.06, fixing cables and slaves: 11.06-11.11, moving forward :11.11-11.16, preparation of rollers:11:16-11.25, fixing cable :11.25-11.28-11.30, moving beam forward:11.30-11.37, shift siding: 11.37-11.41, moving forward: 11.41-11.45, fixing holders:11.45-11.48, moving beam forward without truss:11.50-11.51, side shifting the truss to the left: 11.55-11.59,start moving down the beam at 11.59	(beam no.39):11.37-11.41

Table 5.8 Preliminary observations of work process: Field Note 3

Beam Arrival to Site	Beam available in site	Delivery operation	Erection operation	start of erection	erection finished toward placement
		Beam Number	Beam Number		
	37,28	37,28	37	erection operation of beam number 37 start at 12.40	beam 37 placed at 15.00
05.30 , 14.00	38,28	35, 39	35	erection operation of beam number 35 start at 10	beam 35 placed temporarily at 13.00
	38,28,39		39/		start to place down the beam no. 39 at 11.59-12.25, there is no enough space to finalize the placement of beam therefore they did side shifting again from13.30 and permanent placement completed at 14.23

Table 5.9 Preliminary observations of work process: Field Note 4

Extra works on beam: for eg., releasing the lifter holders, installation of packs etc.	returning back the gantry to be ready for next beam	continue progress on the beams which are placed temporarily	duration	Types of Beam		Placing	
				Edge	Intermediate	Temp	Perm
15.00-15.30	15.30-16.00				√	√	
13.00-14.00				√		√	
releasing the holders 12.25-13.30, check the level of placed beam: 14.23-14.55, releasing the holders (start after smoko) : 15.30-16.20	side shifting the truss to right side to make it ready to be back : 16.20-16.25	Preparation of beam no. 37 starts at 16.25 by fixing the holders on that beam and continues till 16.40. fixing lifting frames:16.40-16.50, side shifting the truss to the left side:16.50-16.53---17.13, moving truss forward: 17.13-17.15. preparation the support where the beam should be placed on: 17.15-17.25, moving the truss to the right side and then fixing the lifting frame on the previous beam (35) + preparation of the support: 17.25-18.20, moving beam 35 back toward SA:18.20-18.30, toward finalizing the holders on the top of beam 35: 18.30-19.00		√ (39)			√

Table 5.10 General version of spreadsheet database

Project	Waterview Connection	
Recorded by	Name	Eunsub Ko
	Position	Site Engineer

Operation hours			
Date	Start	Finish	Smoko
20/08/2015	7:00	12:30	0:00

Beam placement (directly associated)															
Activity type	Beam Number	Span Number for the beam	Gantry location at start of shift	Delivered span	Beam Delivery		Preparation work on delivered beam		Self launching (note finish = on placement span locked on central/placement anchors)		Beam Placement	Return time/Parking time		Parking span	Number of spans travelled
					On site	Unloaded	Start	Finish	Start	Finish	Finish	Start	Finish		
Infill placement	459	12	9= P9, P10 and P11	8	8:50	9:20	9:50	10:20	11:15	11:45	12:00	12:00	12:20	11= P11, P12 and P13	5

Crosshead preparation					
Location	Activity	Type of plant/ equipment	Number of workers	Start	Finish
R4P12 & R4P13	Crosshead preparations	JLG	2	7:30	8:30

meetings				
type	reason	start	finish	who
Pre-start	Start of shift to discuss hazards and sequence of works	7:00	7:30	all
Smoko	Eat			all

comments (include delays, incidents etc)

Date: 26/8/15
Start: 7:00 pm
Finish 4:30 am (Gantry crew) & 4:30 am (Ravi crew)
Smoko: 0:30

Nightshift
- **Colin/Gantry crew**

Remove R4P9 and R4P10 runway beam.
Ramp 4 span 10 pour assist
Cleaned up Little flint

- **Ravi/Tabletop**

Ramp 4 span 10 pour assist

Incidents/Delays

Parking position
R4P11, R4P12 and R4P13 (far East as possible for rear end)

Thursday
- **Colin/Gantry crew**

R4P10 Tabletop pour assist
Water blast barrier starter locations

- **Ravi/Tabletop**

R4P10 Tabletop pour

Sunday
- **Colin/Gantry**

Strip R4P10 East shutter with Hiab (Note Colin on days from Monday with

- **Ravi/Tabletop**

Strip R4P10 East shutter and infill shutters
Move handrails in on span 10 and strip deck edge boxing

Assistance from day shift
- **Scotty**

50T RT & 25T RT
We should not require 25T RT & 50T RT on nights for a little while Scotty s

- **James**

R4P10 DH16 bars for Eastern flange
Looks like some of top flange hook return bars (DH16?) hasn't been tied
Can you please have steel fixers to tie them so they won't move around

Traffic management
- Steve Kelly

Thursday 27/8/15
Require GNR Full W/B Closure, Including R/T lane on the E/E
Require GNR - EB – GNR On-Ramp Closure,
Require SH16 –EB - Full Closure between GNR to St Luke's
Do NOT Require SH16 –WB - Full Closure between GNR off r

Personnel
- Gantry crew
  Edison, Eti, Johnny H, Kava, Kevin , Rohit, Simon, Sosaia and Quintin.
  No Colin

Misc
- **Plants**

860 WCA JLG in Median
860 WCA JLG in Machete
25T to stay in Median
50T RT crane in Machete with Fly-jib (to be transported to Ramp 4 North abu

Fuelling
N/A

Delivery of beams
Next Delivery
Beam 466 programmed for 15/9/15 @ 5am

Figure 5.1 Customised SharedPoint database template: Data recording

However, Table 5.10 and Figure 5.1 (the last two versions of the database template) enabled the researcher and database users at the studied organisation to have an appropriate directory of information. Information embedded in the template indicated the duration of activity, the operation life cycle, causes for interruptions to processes (constraints) and further information related to resources. This research study could use the collected information indirectly or the operation could use the information directly. In the first case, information on both the duration and sequence of activities was used in the simulation of the gantry launching operation. In the latter case, the data supported the studied case with their "lean" practices, with the Last Planner System (LPS) used as an effective tool. The achievement in this situation is included in the research contribution chapter to corroborate the advantages of the simulation study. The most significant contribution of the study came from identifying the constraints, and breaking down the process plan. One of the advantages was identification of the constraints, with this assisting with LPS implementation and achieving the organisation's objective of the use of "lean" principles. A second advantage was that it helped in gaining a more detailed understanding of the gantry launching operation behaviour, with the additional details used to improve the process schedule.

Other useful data were collected through meetings, emails and the construction organisation database (ORBIT), project method statements, launching operation handbook, pre-start and meeting minutes, project layout (AutoCAD [computer-aided drafting] layout), project master plan and LPS components (e.g. week score plan and look-ahead plan.

The researcher obtained some documents directly while the relevant site engineer for the process and the project planner team sent others by email. The document content provided background information of the processes under study. The combination of the documentary evidence with the data from observation served to minimise bias and establish credibility.

According to Voss, Tsikriktsis and Frohlich (2002), documentation can also include taking notes and/or the transcriptions of tapes. Thus, the researcher took field notes to write up insights gained during field visits and also recorded suggestions and ideas during site visits.

With all required data collected, the study proceeded to the analysis stage. The next sections present and discuss the methods used for data analysis.

5.5 RESEARCH METHODOLOGIES FOR DATA ANALYSIS

As discussed previously, the selected case study provided the current research with the opportunity to use two sources of evidence for data collection. This section discusses the analysis approaches based on these two information sources: participant observation and documentation. The analysis of evidence is one of the least developed and most difficult aspects of conducting case studies (Yin, 2014, p. 133). With regard to the analysis phase of case study evidence, various viewpoints are expressed with one related to the use of statistical approaches. As pointed out by Tellis (1997), statistical robustness is not compulsory in all case studies.

In the data analysis phase, the researcher needs to rely on experience and the literature to present the collected evidence in different ways, using various interpretations

(Tellis, 1997). This is more important when case study research has not used statistical analysis. Furthermore, some alternative techniques suggested by Miles and Huberman (1984) include using arrays to display data, creating displays, tabulating the event frequency and sorting out the information.

The purposes of data analysis are to examine, categorise, tabulate, test or recombine evidence to enable the study to deduce and present its findings (Yin, 2013). As mentioned earlier, analysing case study data is difficult as techniques have not yet been well defined (Yin, 2014). As recommended by Yin (2014): “the researcher can start analysis by “playing” with the data and searching for promising patterns, insights, or concepts – the goal being to define your priorities for what to analyse and why” (p. 132).

The current study, in accordance with its objectives (see Section 1.2.2), applied the following pattern. As the research’s main aim was to explore the capability of EZStrobe simulation, to fit the simulation functions, data required conversion into a particular format. As shown by the EZStrobe discussions (see Chapter 6, Section 6.2, and Chapter 7, Section 7.1.3), to input the duration of the activities, the probability function needs to be identified that could best fit the distribution of the associated data set. Through the literature review, the current study found that recent scholars (Abbasian-Hosseini et al., 2014; Nikakhtar, Hosseini, & Wong, 2012; Nikakhtar et al., 2015; Nikakhtar et al., 2011; Poshdar et al., 2014) had used a specific software program called EasyFit to easily and quickly select the probability distribution which best fit their data.

Selecting the appropriate distribution is a critical success factor in a simulation study (AbouRizk, Halpin, & Wilson, 1994; EasyFit, n.d.). AbouRizk and Hague (2009) and AbouRizk et al. (1994) state that the behaviour of construction operations is subject to a wide range of fluctuations and interruptions. Moreover, construction operations are subject to random variations of these constraints: consequently, during simulation, their modelling will be as random processes. The modelling of a random input process includes selecting and fitting a sufficiently flexible probability distribution to the associated process based on the collected data (AbouRizk & Hague, 2009). As the first step of the data conversion, the collected data were analysed using EasyFit (for an introduction to EasyFit software, see Appendix I). The results were then translated to be fed into EZStrobe.

At the next phase, EZStrobe modelling, the current study first developed an activity cycle diagram (ACD) (through the preliminary study phase), with the model then run using EZStrobe's "Function Builder" capability. The formulation of assumptions for the model development in EZStrobe, and the process of analysing and interpreting the output, and developing the framework for the implementation of EZStrobe are presented and discussed in the next chapter, and together comprise parts of the analysis approach undertaken by the current research. Two main capabilities, namely, statusing and scenario analysis were major concerns of the current study, with these explored using the animation and model elements functions of EZStrobe. Chapter 6 and Chapter 7 present the relevant discussions.

Using an analysis pattern (see Figure 5.2) enabled the study to cover the knowledge gap and achieve its objectives.

To develop this data analysis pattern, it was necessary to sort out the data collected from participant observation and documentation. The current research applied Yin's (2014) principles, as discussed in Section 5.3.3. Consequently, this assisted the study in enhancing the reliability, ease of use and preparation of data for the analysis step. In addition, another phase, the complementary phase, discussed in the next section, had these principles embedded.

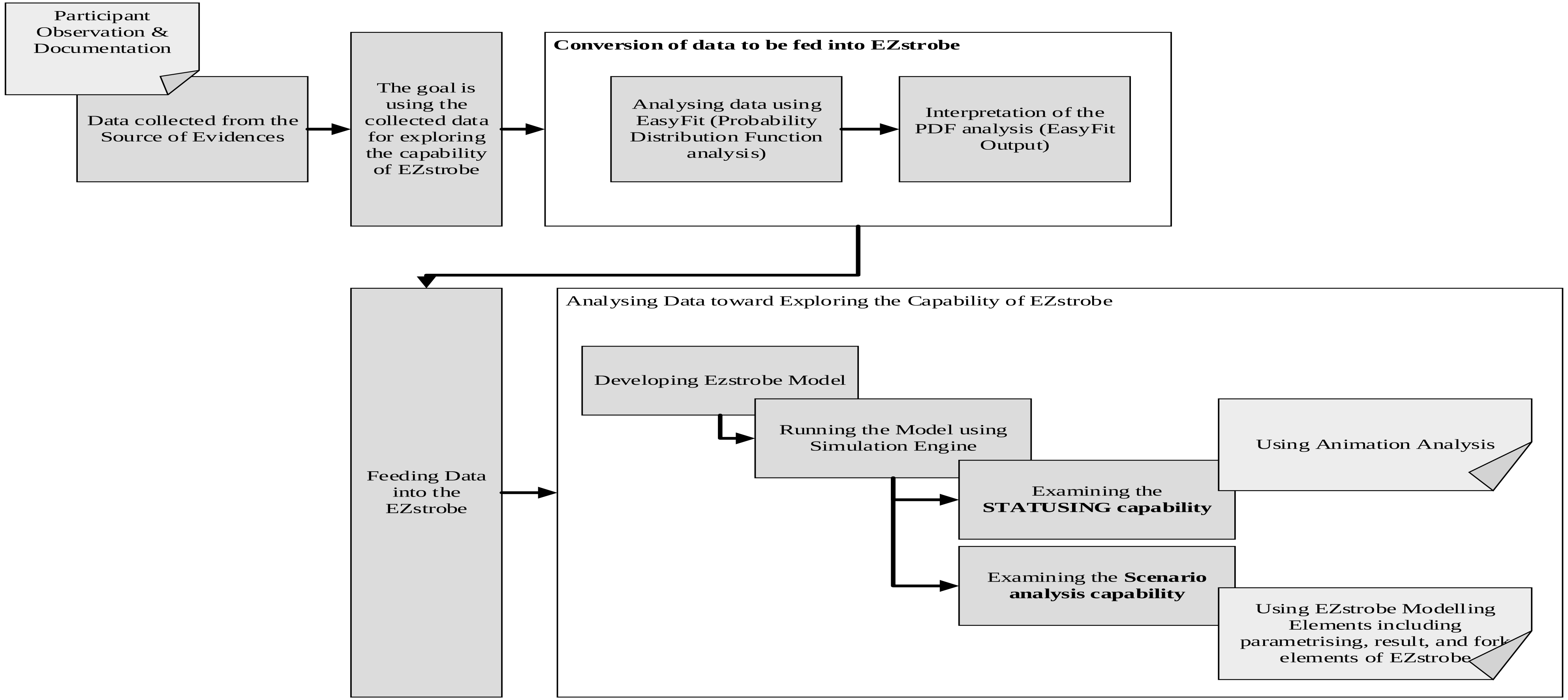


Figure 5.2 Data analysis pattern for current research study

5.6 REPORTING THE CASE STUDY/COMPOSITION

According to Yin (2014) and Rowley (2002), the last step in a case-based research study is writing the case study report. Rowley (2002) suggests that this might be a daunting task, as the researcher needs to discriminate between what is to be included and the wealth of data in the case study database, not all of which is to be included in the report. Furthermore, the researcher is required to structure the report applying effective analysis (Rowley, 2002).

The aim of reporting the case study is to share the conclusions from the studied case, and to bring its results and findings to a point of closure (Yin, 2014).

A key factor in this phase is determining the audience (Rowley, 2002; Yin, 2014). Different audiences, such as academic colleagues, practitioner professionals, research supervisors and examiners, have different expectations and needs. For example, for dissertation assessors or a thesis committee, the researcher's mastery of methodology and understanding of the way that the research contributes to existing knowledge are important (Rowley, 2002).

According to Yin (2013), to carry out good case study research, the researcher needs to answer these questions: what should be composed, and how? The successful researcher usually perceives this phase (the compositional phase) as an opportunity to share the contribution of the study with others (Yin, 2013). It is important to note that composing is part of reporting the case study and differs from writing. Composing the case needs creativity and flair. However, the term "composing" does not mean that the researcher is writing a novel (Yin, 2013). Any reference to the features of good fiction like "storytelling" and "dramatising" may lead the audience to question the validity of the research and its interpretations (Yin, 2013). However, Yin recommends that the researcher think about the non-fiction style as the counterpart craft at this phase. In this context, Barzun and Graff (1985) and Wolcott (2009) offer this invaluable advice: take notes, make outlines, use plain words, establish a schedule for composing, write clear sentences and combat the common urge to not compose.

Accordingly, the final composition should reflect emphases, details, compositional forms and a report length suitable for the potential audience (Yin, 2013).

Another key point in successfully sharing a case study report is to examine other case studies that have successfully shared their findings with the same audience/s that you (as a researcher) intend to reach in relation to your study (Yin, 2013).

In comparison to other types of research, the case study report itself can be a significant communication device in any case-based research study (Yin, 2013). Single case study designs reportedly raise awareness and provide insights to non-specialists: they can even suggest solutions to a given situation. This type of case-based research could use simple but appealing non-textual materials such as photos and graphics. Such a presentation could be helpful in gaining an understanding of a phenomenon, especially in the case that the array of statistics—no matter how compelling to a research audience—cannot do the trick (Yin, 2013). In this way, the case study enables the communication of research findings to various non-specialists instead of only targeting research colleagues as is done with the typical research report (Yin, 2013). The following sections describe how the data collected from participant observations and documentation have been processed and presented at the final step of this case-based research.

5.6.1 PARTICIPANT OBSERVATION

After each process study, the data were categorised and recorded in an MS Excel spreadsheet. Using the spreadsheet database made it easier to analyse the data and helped to provide a better understanding of the process as well as allowing for later access to the data for further analysis (i.e. in simulating the operation).

The collected data that related to the duration of activity needed to be analysed to provide a specific insight into the operation behaviour. As mentioned earlier, this part of the data analysis used EasyFit software.

Through using the data processed by EasyFit as input for EZStrobe, the current study could simulate the gantry launching operation and develop a framework for the implementation of EZStrobe. The second round of modelling operations using the two data sets collected over the construction of both Ramp 1 and Ramp 4 had verified this implementation. Moreover, maintaining the record of evidence and customising the organisation's database allowed the study to contribute to the improvement of the operation's productivity through:

1- Facilitating the tracking of performance and consequently updating the project master schedule (PMS): continuing to analyse the collected data and constructing the simulated model provided the study with the opportunity to warn the organisation about different constraints: these could possibly occur quite often in this particular operation. Therefore, the research study was able to report to the Site

Superintendent and share the insights gained from running the simulation model, as well as what the study had identified as barriers/constraints affecting the progress of the project.

2- Improving LPS practice: through applying more reliable data, additional constraint analysis, etc. To corroborate its reactive role in operations productivity, the study also sought to apply some of the automated solutions for the specific database being used for LPS by the organisation.

5.6.2 DOCUMENT ANALYSIS

After receiving permission to access the case study organisation's database and required project documents, the study conducted a thorough document analysis. The following documents provided various aspects of data that were analysed for the current study's purposes:

a) Operation's Manual Handbook: this contained information on the twin-truss gantry machine: the components of the machine; machine assembly; remoting the machine; maintenance; required conditions for the use of the machine; and restrictions on the use of the machine

b) Sequences of the work operation for the delivery of beams on Ramp 1/Span 7

c) MS Project schedule: master schedule in MS Project format

d) MS Excel spreadsheet: week score plan and look-ahead plan

e) AutoCAD layout: project layout and details in CAD format

Access to these information areas helped in gaining a general idea on the gantry launching operation, and in analysing the differences between standard operating procedures (SOPs) and the actual working procedures at the case study site. Analysis of some of the documents two months prior to the commencement of the gantry launching operation helped the researcher to identify the necessary data and the opportunity for improving the WBS, and to develop a database for recording data and a WBS based on the simulation language (the ACD). The findings of the document analysis at this step, gained in the period from November 2013–January 2014, were used to verify the observations made at the site during the process studies (January 2014–September 2015). Composing this information into illustrative formats, such as the diagrams developed in the preliminary study (e.g. the initial WBS and ACD), supported the current study with communicating its findings on the developing WBS for the gantry launching operation and, subsequently, in answering research questions 1 and 2 (see Section 1.2.3).

In completing the current research report, the researcher considered the research objectives, the study's contribution to existing knowledge and the need to address the knowledge gap: the discussions in Chapter 8 present this report.

5.7 RELIABILITY AND VALIDITY IN CASE RESEARCH

The quality of case study research has attracted many criticisms, some valid, some invalid (Stuart et al., 2002). As emphasised by Voss et al. (2002), it is important to pay attention to reliability and credibility in case-based research. Stuart et al. (2002) and Yin (2003) add that reliability and validity have the following dimensions:

1- Construct validity: is the extent to which the researcher establishes correct operational measures for the studied concepts. In this vein, Leonard-Barton (1990) says that "if the construct as measured can be differentiated from other constructs, it also possesses discriminant validity". The main criticism of the case study approach is the lack of construct validity due to the subjective judgement used for data collection (Yin, 2003). To ensure that researcher bias is eliminated requires appropriate steps to be taken. Using multiple sources, establishing a chain of evidence and having key informants review draft case study reports are ways to eliminate researcher bias in a case study (Yin, 2003).

   Furthermore, four ways have been recommended by Voss et al. (2002) to test construct validity. These tests are:

   1-1- Checking that the predictions made about the relationships to other variables are confirmed;

   1-2- Using multiple sources of evidence;

   1-3- Checking that the construct as measured can be differentiated from another construct; and

   1-4- Searching for triangulation that may strengthen construct validity.

2- Internal validity: concerns the approximate truth about inferences regarding cause-and-effect or causal relationships. According to Yin (2003), it is possible to achieve internal validity at the data analysis phase by using pattern matching and explanation building, and addressing rival explanations and logical models. In the same vein, Shenton (2004) states that the researcher can improve the credibility of case-based research by adopting appropriate research methods including negative case analysis, early familiarity with the culture of the participant and examining the previous research. Furthermore, Shenton (2004) believes that introducing different provisions at the data collection phase, such as random sampling of participants, debriefing sessions to the project organisation and triangulation of different types of informants and different sites can help with the improvement of the research's credibility.

3- External validity: is the extent to which the researcher understands whether the research findings can be generalised beyond the immediate case study (Voss et al., 2002; Yin, 2003). It has been claimed that the external validity of single case-based research studies is lower than their internal validity (Yin, 2003) as the findings of a single case study are specific to a particular setting and participants.

4- Reliability: "is the extent to which the study's operations can be repeated, with the same results" (Yin, 1994, p. 36).

5.7.1 ACHIEVING RELIABILITY AND VALIDITY IN THE CURRENT RESEARCH

To achieve reliability and validity in the current research, the suggestions of Yin (1994, p. 33) (see above section) were applied in different phases of the research. Table 5.11 presents how this research study adopted Yin's test.

Table 5.11 Adopting Yin's test to achieve reliability in current research

Test	Research phase	Case study tactics in current research
Construct validity	Data collection	1- Using multiple sources of evidence (see Section 5.5), including participant observation and documentation. 2- Maintaining the chain of evidence by attending follow-up meetings; constant on-site participation when the process was occurring (for two process operations: Ramp 1 and Ramp 4); note taking at meetings and during site visits; and developing and customising the organisation's database (described in Section 5.5)
	Composition	1- Presenting the key contribution of the research's findings through the report, meetings, analysis, diagrams and graphs 2- Giving publications, the report and analysis to key informants for review
Internal validity	Data analysis	The data analysis pattern followed the two main analysis approaches: EasyFit for probability distribution function (PDF) analysis and EZStrobe as the simulation approach for statusing and scenario analysis (see Section 5.6). As the model development using simulation (see Section 7.1.2) was done by formulating assumptions on the operation behaviour, comparison analysis later became feasible. In comparison analysis, the behaviour of operations in the real world (the concept of the study gained through both documentation and field observation) was compared to the results of the simulated operation.
External validity	Research design	Studying two rounds of the gantry launching operation in the construction of Ramp 1 and Ramp 4 was included in the research design. This enabled the study to normalise the simulation model developed for the operation, and to generalise the framework for the implementation of EZStrobe in construction operations.
Reliability	Data collection	Utilising the same data collection procedure for each studied process; field study notes; developing the case study database to have a consistent set of data in a consistent format.

5.8 RESEARCH ISSUES

5.8.1 LIMITATIONS OF THE RESEARCH

As discussed earlier, the current research study was designed around obtaining data from a single case. Although the results of a case study have very high impact, several challenges arise in conducting case-based research; for example, it is time consuming; skilled interviewers are required; and drawing generalisable conclusions from a limited set of cases is not easy (Voss et al., 2002). According to McCutcheon and Meredith (1993), the case study approach is one of the empirical approaches which aim to develop an understanding of real-world events. In addition, different types of empirical investigation derive their strength from focusing on actual events, or on actual conditions. However, using an organisation as a case study makes the use of such approaches difficult. The reason is that conducting the case study (e.g. in the form of fieldwork) on ongoing operations does not allow the researcher to control conditions to affect the outcomes. The researcher, therefore, must study the phenomenon by noting the states in each case and be aware of all conditions that may affect outcomes. Familiarity with the conditions which are likely to be occurring, on one hand, and conducting a case study using a large number of cases, on the other hand, lead the research to employ quasi-experimental methods. In this situation, the possible impacts of conditions can be taken into account (Campbell & Stanley, 2015). In contrast, when dealing with unfamiliar situations, or situations with little theoretical background, the researcher may not know which conditions are relevant or important. Moreover, the number of cases which can be investigated might be very small, especially compared to the number of conditions that must be considered (Yin, 1994). In such circumstances, the case-based research may be the only means to investigate a problem. One of the most typical situations for which the case study approach has been recommended is to describe a hitherto unstudied situation or to explore that situation (Yin, 1994).

With the main objective being to explore EZStrobe's capabilities, the current research experienced the limitation of needing to access different construction operations. Other limitations are as listed:

1- Focus needed to be on the challenges related to productivity and operations management where a new method of construction was being used.

2- Conformance required between the time schedule for conducting the current research and operations. The start and finish time of the ongoing operations could allow the study to follow up the exploratory procedure, collect data and account for further data collection if any data were missed due to unfamiliar situations.

3- Limited number of construction organisations that were seeking an investigation on their potential to improve project productivity at the time when this research was about to start its fieldwork study.

Consequently, only one organisation was able to provide the opportunity to conduct this research study. Therefore, the current study did not have the opportunity to identify a critical case to enable the generalisation of the study's findings through statistical analysis. The validity of generalisations drawn from a single case-based research study has attracted criticism; however, this design has been used extensively for exploring new technology within the construction literature (Flyvbjerg, 2006). In response to criticism from some scholars and research advisers, Flyvbjerg (2006) proposed that selecting an "extreme case" could be an approach well suited to a single case-based research design. Extreme cases for research could be identified as those that are "especially problematic" in a certain area. Considering the level of complexity of the current study's selected case and the newness of the method of construction and simulation experiment intended for deployment in the project, this case study was deemed a rare case. According to Flyvbjerg (2006), it is incorrect to conclude that a single case study cannot be generalised. The generalisation and validity of the single case depend on the particular case and the method used to choose it. Therefore, in response to such limitations, the current research applied an analytical pattern. Through developing a framework for the implementation of EZStrobe, the EZStrobe model was verified and normalised, consequently, providing an opportunity for generalisation in further empirical studies through contributing to "lean"/LPS practices.

5.8.2 RESEARCH ISSUES: ETHICAL ISSUES

With the current research design based on the case study approach, ethical considerations were of fundamental importance. Therefore, prior to commencing the fieldwork study, the researcher submitted an ethics application to the Auckland University of Technology Ethics Committee (AUTEC). The current study considered ethical issues at all stages of the research design and execution process.

The researcher explained the research objectives to those of the organisation's members who were engaged in the specific part of the project about which the study was concerned (the gantry launching operation). The crews were informed that the study was being undertaken for the purpose of completion of a PhD degree, and that their assistance, in terms of providing and sharing project information, reviewing the report over the period of study and giving feedback was voluntary. In addition, the crews were informed that they had the right to accept or decline participation at any time during the study.

Participants received assurances that the study would observe their rights to privacy, confidentiality and anonymity. If the study required any video recording or taking of photos, footage or photos of the crews would not be included. All video recording and photos would be set to zoom in on the resources (with the exception of human resources) and on the operations process. The information gathered would be kept confidential and not disclosed to anyone except the researcher and project supervisors. Furthermore, any information related to the organisation and that specific group was not be shared or discussed with any of the organisation's other teams.

5.9 SUMMARY

This chapter clarified the logic behind the selection of the paradigm, approach, strategy and methodologies that the current study utilised. The research method and techniques were selected to enable the researcher to answer the research questions and to achieve the objectives of the research. Figure 5.3 below presents the research design applied to the current study.

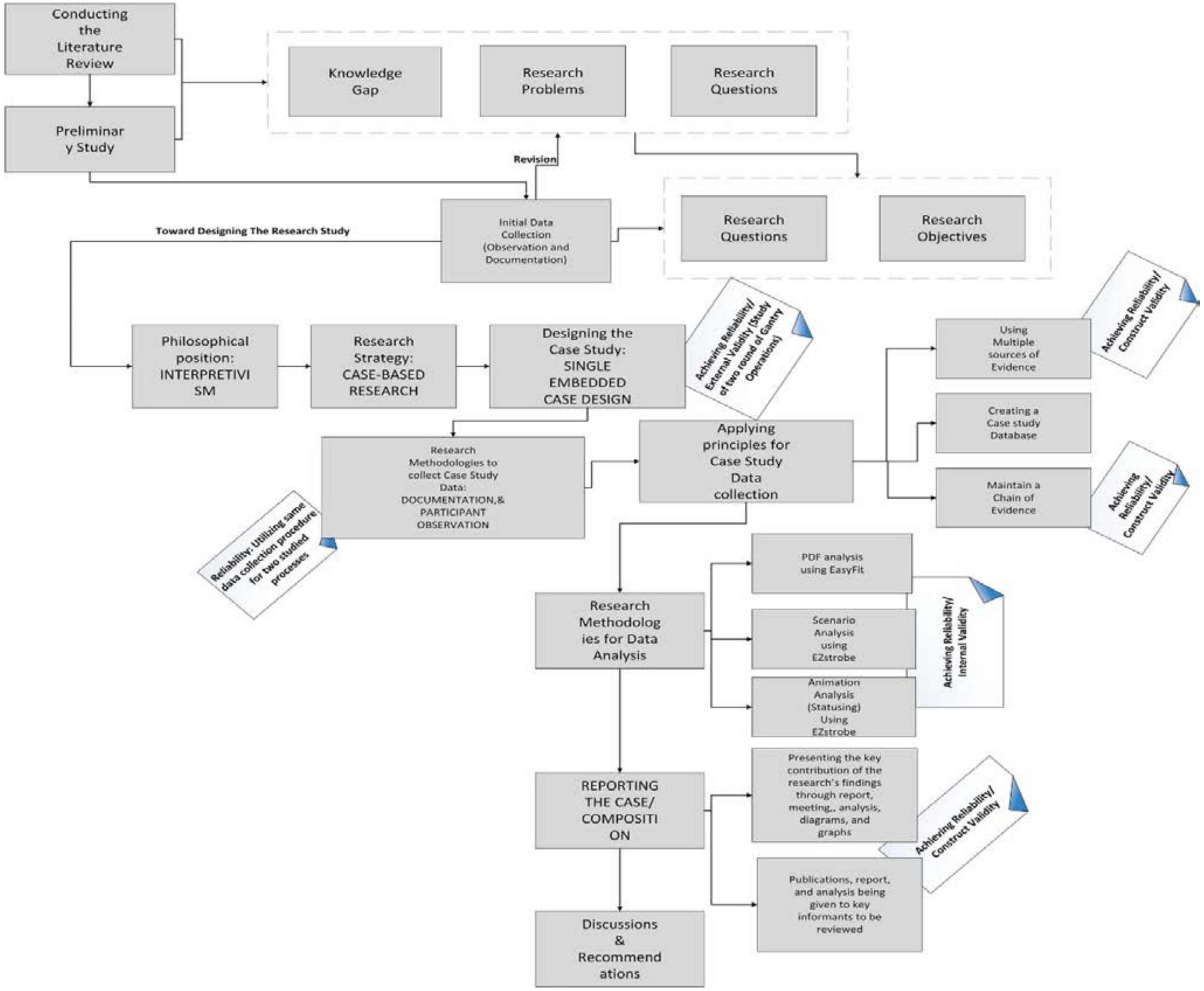


Figure 5.3 Framework for current research study

As shown on Figure 5.3, the study started with conducting the literature review analysis and the preliminary study to identify the knowledge gap and the research problems. This led to formulation of the initial research question. When the fieldwork study commenced, the researcher was in the position of being able to revise the research objectives and research questions.

Once the areas of concern were understood, the research then progressed to a new phase in which the researcher designed the research study. As discussed earlier, the current research selected the interpretivist paradigm. Continuing with the design, the selection of the strategy and methodology followed. With the case study approach selected, the study took account of applying the principles and achieving reliability in all associated steps. The notes tagged to the details of the research framework in Figure 5.3 indicate the links between the research design and achieving reliability. Each tag illustrates how the details considered in the research design supported the study in achieving validity (including construct validity, and internal and external validity) and reliability. Finally, as shown in Figure 5.3, publications, reporting, discussions and recommendations completed the study, with these included in Chapter 9, Appendix 2 and Appendix 6, respectively.

CHAPTER 6

DATA COLLECTION AND ANALYSIS:

(I) THE PRELIMINARY STUDY

6.0 INTRODUCTION

This chapter presents the data collection and analysis processes undertaken in the preliminary phase of the study. As previously discussed, along with the literature review analysis, conducting the preliminary study helped the research by assisting with formulating the research objectives and research questions.

The first section of this chapter introduces the case study project. The following sections present the construction methodology and planning approaches used by the studied organisation. As the current research aimed to explore the capability of EZStrobe, the chapter next introduces the environment of that program.

The remainder of this chapter describes the processes used for data collection and analysis in simulating the selected operation (the gantry launching operation) within the case study project.

6.1 DESCRIPTION OF THE CASE STUDY

The selected case is part of one of the most important infrastructure projects in New Zealand. The project involves the construction of a motorway ring route around Auckland to unlock Auckland’s potential to become a truly world-class city (NZ Transport Agency, 2016). The two main project sections in this case study project are:

1- The construction of a 48 kilometre (km) motorway comprising two main sections: the Waterview Tunnels comprising twin 2.4 km tunnels that will each carry three lanes of traffic, and

2- The Great North Road Interchange (GNRI): four ramps that total 1.7 km in length to connect the Southwestern and Northwestern motorways (State Highways 20 [SH20] and [SH16], respectively) immediately north of the tunnels to complete the Western Ring Route.

The case study area is part of Section 2 where four ramps at the motorway interchange provide connections between the Waterview Tunnels and SH16 (see Figure 6.1). The sections that follow then present further details about these four ramps.

The main reasons motivating this study to select the gantry launching operation as a main part of the project to be simulated were:

1- Absence of a WBS on the bridge launching operation

2- Absence of any previous simulation study in which an EZStrobe model was developed for a bridge launching operation

3- Need to improve productivity in typical operations in New Zealand by focusing on IT integration.

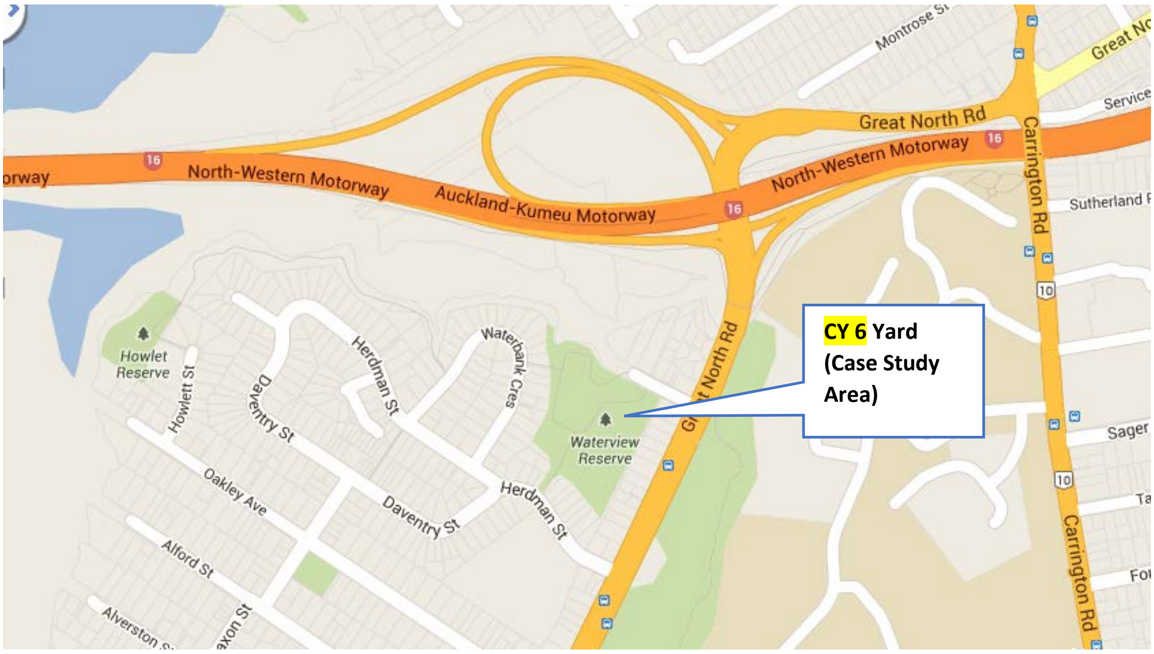


Figure 6.1 Case study location

The snapshot provided in Figure 6.2 has further details of the case study project, including the layout of the GNRI ramps. In Figure 6.2, there are four ramps labelled Ramps 1–4. Each ramp was designed to convey traffic on and off the SH20 motorway in various directions (Western Ring Route, Northwestern motorway and Southwestern motorway).

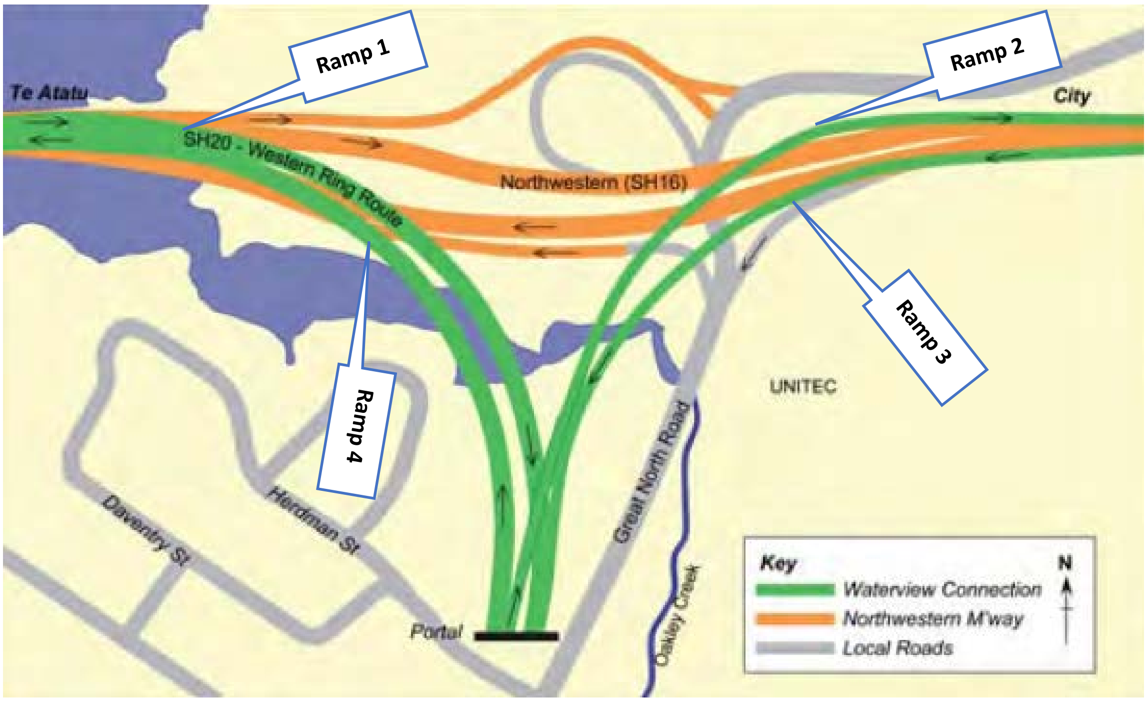


Figure 6.2 Layout of the GNRI ramps

The construction methodology for all four ramps comprises 1,525 mm deep precast pre-stressed super T-girders, installed using a twin-truss gantry machine.

Geometric constraints, local topographical features and the need to minimise impacts on the Coastal Marine Area (CMA) dictated the bridge span arrangements. The super-T girders were pushed to maximise the span lengths, with a preference noted for minimising structural depths to reduce approach ramp grades.

A prefabrication company (Wilson) precast the super T-beams: the company then delivered each beam to the CY6/GNRI area using a specific type of truck (truck and jinker). To deliver the beam, the truck needed to access the gantry area through a clear pathway. The gantry crane then picked up the beam from the truck, after which the unloaded truck could then leave (see Figure 6.3 and 6.4).

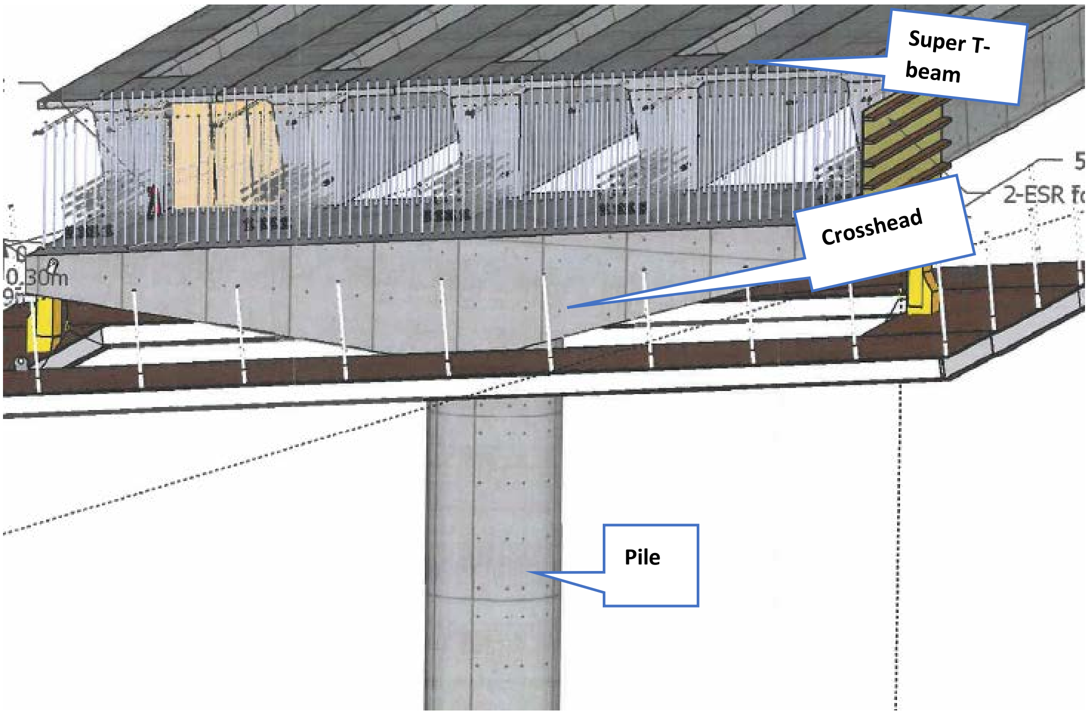


Figure 6.3 Main components of the ramps

Figure 6.4 Truck and jinker delivering precast super T-beam

As mentioned above, the methodology for the construction of GNRI ramps was a girder launching operation using a twin-truss gantry machine. For the selected part of the operation related to the current research study, the gantry machine was the main equipment. This machine, designed specifically for the construction of these four ramps, could work with different span lengths, with its main components as follows:

1- Main truss
2- Rear and front lip
3- Main truss anchor system
4- Erection supports
5- Auxiliary supports
6- Master and slave winches
7- Anchoring systems

The general information on Ramps 1 and 4 is summarised in Table 6.1 and Table 6.2. The tables present the number of spans included in each ramp, the span's length, the number of beams included in each span and the sequence of the delivery of beams as well as their placement (see also Figure 6.5 and Figure 6.6).

Table 6.1 Details of information on Ramp 1

Span number	Length of span	Pier number	Number of T-beams	Beam number	Edge (outer) beam	Sequences of beam delivery to site	Sequence of beam placement
Span 7	25750	Pier 6 and S. Abutment	5	35 to 39	35, 39	1- 37, 2- 35, 3- 39, 4- 36, 5- 38	35 (P), 37 (T in 36), sideways and permanent placement of 37, 39 (T seat), 39 (P seat), 36 (P), 38 (P)
Span 6	25750	Piers 5 and 6	5	30 to 34	30, 34	1- 32, 2- 30, 3- 34, 4- 31, 5- 33	32 (P), 30, 34, 31, and 33
Span 5	34700	Piers 4 and 5	6	24 to 29	24, 29	1- 26, 2- 27, 3- 24, 4- 29, 5- 25, 6- 28	26, and 27, then 24, 29, 25, and 28
Span 4	34700	Piers 3 and 4	6	18 to 23	18, 23	1- 20, 2- 21, 3- 18, 4- 23,	

Span number	Length of span	Pier number	Number of T-beams	Beam number	Edge (outer) beam	Sequences of beam delivery to site	Sequence of beam placement
						5- 19, 6- 22	
Span 3	34700	Piers 2 and 3	6	12 to 17	12, 17	1- 14, 2- 15, 3- 12, 4- 17, 5- 13, 6- 16	14, 15, 12, 17, 13, 16
Span 2	36930	Piers 1 and 2	6	6 to 11	6, 11	1- 8, 2- 9, 3- 6, 4- 11, 5- 7, 6- 10	
Span 1	28000	N. Abutment and Pier 1	5	1 to 5	1, 5	1- 3, 2- 1, 3- 5, 4- 2, 5- 4	
Ramp 1 length	220530	Six piers and two abutments	39				

Table 6.2 Details of information on Ramp 4

Span number	Length of span	Pier number	Number of T-beams	Beam number	Edge (outer) beam	Sequence of beam placement
Span 1	26800	S. Abutment and Pier 1	5	1 to 5	1, 5	Not provided in the instructions.
Span 2	32500	Pier 1 and Pier 2	5	6 to 10	6, 10	
Span 3	32500	Pier 2 and Pier 3	5	11 to 15	11, 15	
Span 4	32500	Pier 3 and Pier 4	5	16 to 20	16, 20	
Span 5	32500	Pier 4 and Pier 5/6	5	21 to 25	21, 25	
Span 6	33250	Pier 5/6 and Pier 6	5	26 to 30	26, 30	
Span 7	33250	Pier 7 and Pier 8	5	31 to 35	31, 35	
Span 8	33250	Pier 8 and Pier 9	5	36 to 40	36, 40	
Span 9	44000	Pier 9 and Pier 10	6	41 to 46	41, 46	
Span 10	44000	Pier 10 and Pier 11	6	47 to 52	47, 52	
Span 11	32500	Pier 11 and Pier 12	5	53 to 57	53, 57	

Span number	Length of span	Pier number	Number of T-beams	Beam number	Edge (outer) beam	Sequence of beam placement
Span 12	32500	Pier 12 and Pier 13	5	58 to 67	58, 67	
Span 13	32500	Pier 13 and Pier 14	5	63 to 67	63, 67	
Span 14	32500	Pier 14 and Pier 15	5	68 to 72	68, 72	
Span 15	26800	Pier 15 and N. Abutment	5	73 to 77	73, 77	
Ramp 4 length	501350	Fifteen piers and two abutments	77			

The process of the bridge launching operation started from the south (S) abutment with the construction of Ramp 1. The operation then continued toward the north (N) abutment. With the construction of the first ramp completed, the gantry machine, after being moved back to the south abutment, would then be prepared for the next round of the operation.

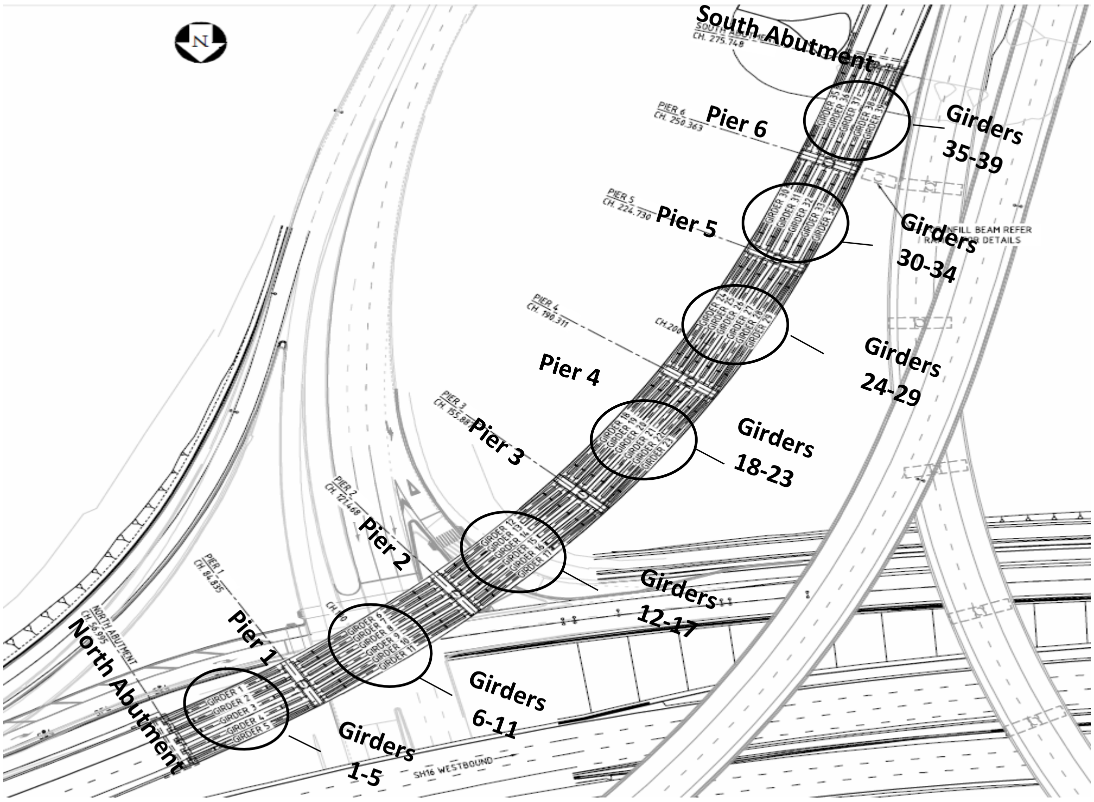


Figure 6.5 Layout of Ramp 1

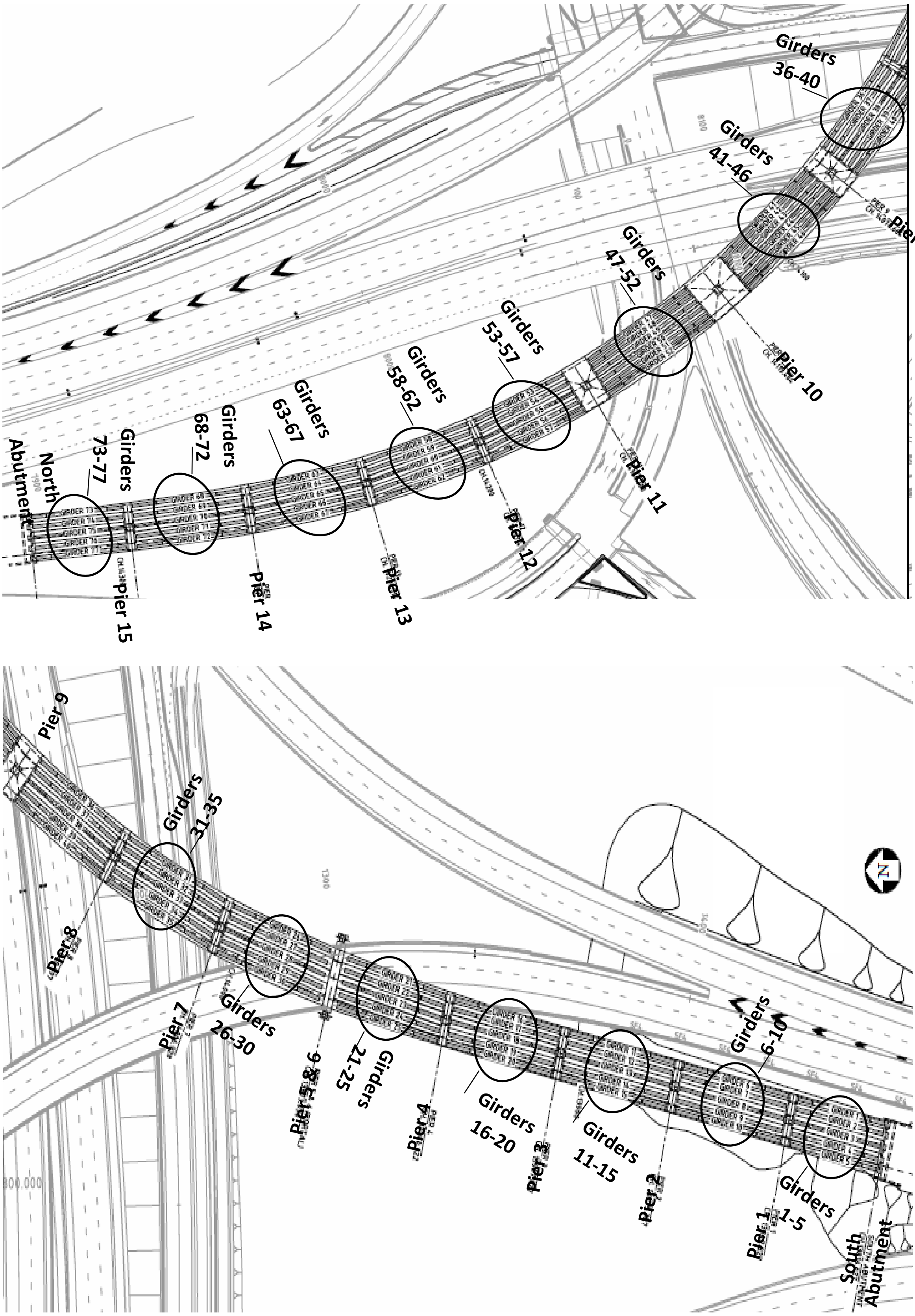


Figure 6.6 Layout of Ramp 4

The supplier of the gantry machine provided the project with instructions on the delivery of super T-beams for Section 1 (Span 7/Ramp 1). As shown in Figure 6.7 and Figure 6.8, the workflow described by the supplier was translated into a flow chart.

As shown in the flow chart, prior to delivery of the first super T-beam, the south and north abutments' bearing plinths needed to be constructed and the location of the centre line of each super T-beam needed to be marked. The delivery time and traffic closure should then be arranged to enable the truck and jinker to deliver each super T-beam to the gantry area. This was necessary as the truck delivering the super T-beam could not be on the road during peak traffic times (7 am–10.30 am). Moreover, it was necessary to confirm the delivery time in advance. No vehicles at the site could park in the travel path of the loaded truck. In addition, no vehicles could park on the bridge deck, if applicable.

In order to accomplish delivery, the truck with each super T-beam should turn left towards the surge pile and then reverse up the hard-fill approaches towards the abutment. The truck should then reverse between the auxiliary supports so the beam can to be placed centrally between the auxiliary support and the runway beam.

The number of the precast beam and its location should be double-checked upon delivery. The gantry crew would then be able follow the appropriate instructions as several features, such as type, length, shape, etc., could influence the placement methodology from the delivery through to placement of the beam on its location over the bridge span.

If a delivered beam is an edge beam, prior to launching the beam to the top of the span, the installation of the edge beam clamps should be completed. The angles of the super T-beam hooked by the gantry machine should be properly adjusted before starting the launching operation. The commencement of launching the loaded gantry and moving the beam to the span where it should be placed once again depend on the type of the beam, and whether the placement operation is for a temporary or a permanent placement. For instance, for the edge beam, a temporary placement is undertaken first; the beam is then side shifted into its permanent position. After the beam is placed in its correct position, the gantry machine should be driven back to its primary location and locked to auxiliary support.

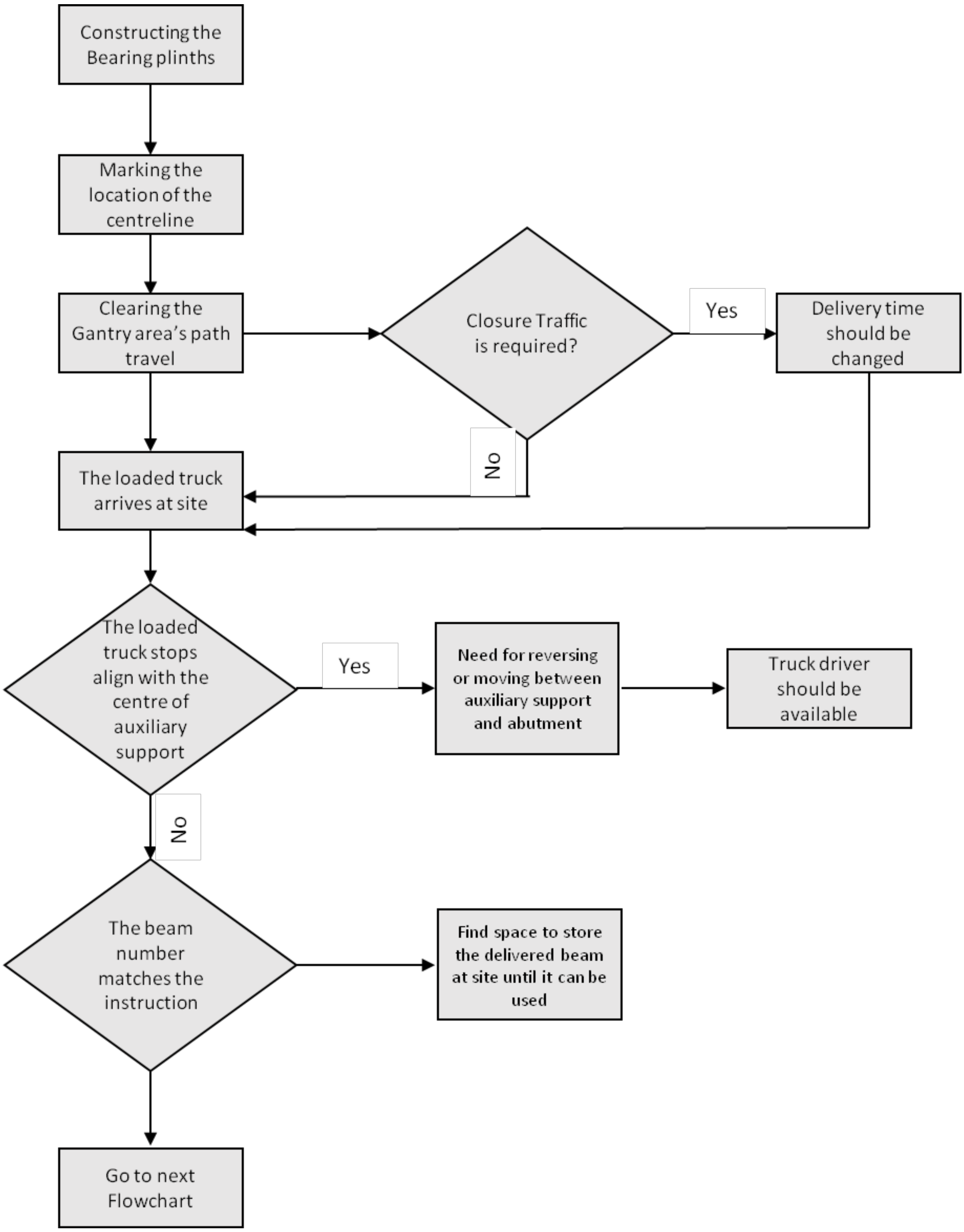


Figure 6.7 Process of beam delivery to site (from gantry supplier's instructions)

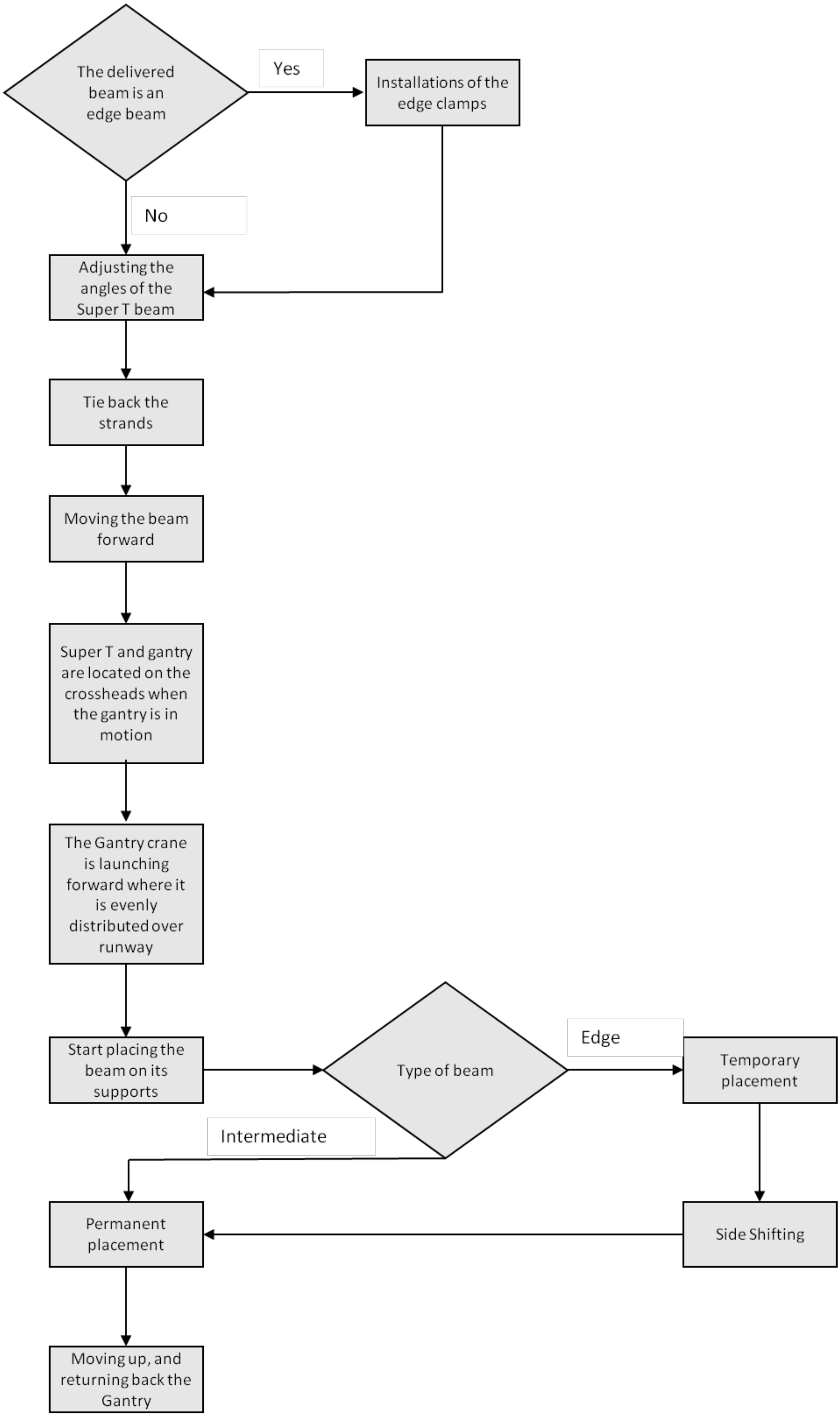


Figure 6.8 Continued process from delivery to placement of beam

6.1.1 CONSTRUCTION PLANNING APPROACHES IN THE CASE STUDY

The planning and management approaches and tools used in the studied case project include the use of MS Project for developing the master schedule and the use of the Last Planner System (LPS) for tracking performance. As previously mentioned, the launching operation was a new method that the project was using. Therefore, the initial master plan was developed based on instructions provided by the gantry supplier (as discussed above).

In the initial master plan, the activities related to the delivery and placement of beams on the first span of Ramp 1 were planned as presented in Figure 6.9.

Task Name	Duration	Start	Finish	Predecessors	Resource Names
Receive super T 37 and install	20 days	Tue 11/02/14	Mon 10/03/14		
Receive super T 35	1 day	Tue 11/02/1	Tue 11/02/1		
Install side forms and handrails super T 35	1 day	Wed 12/02/14	Wed 12/02/14		
Place super T 35	1 day	Wed 12/02/1	Wed 12/02/1		
Receive super T 39	1 day	Wed 12/02/1	Wed 12/02/1		
Install side forms and handrails super T 39	1 day	Thu 13/02/14	Thu 13/02/14		
Place super T 39	1 day	Thu 13/02/1	Thu 13/02/1		
Receive and install super T 38	1 day	Fri 14/02/14	Fri 14/02/14		
Receive and install super T 36	1 day	Mon 17/02/14	Mon 17/02/14		

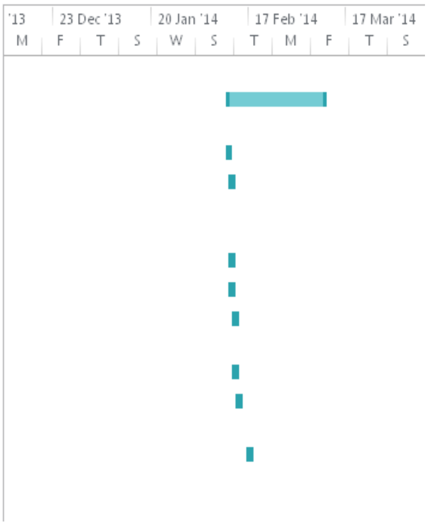


Figure 6.9 Initial master plan for construction of Span 7/Ramp 1 (developed by case study's planner team)

The system metrics used in the developed master plan were on a "daily" basis. The tasks had not been planned in detail; therefore, they did not clearly address all conditions and interdependencies as per the gantry supplier's instructions.

Later sections in the chapter present and analyse the data from the extant key documents in the case study project, in addition to the data from observation. With the research study's aim of exploring the capability of EZStrobe simulation, an introduction of the simulation program is presented next: an understanding of the selected program is helpful for the discussions in the analysis section.

6.2 INTRODUCTION TO EZSTROBE PROGRAM

EZStrobe is an entirely graphical discrete-event simulation (DES) system based on extended and annotated activity cycle diagrams (ACDs) and the three-phase activity scanning (AS) paradigm (<http://www.EZStrobe.com/2009/10/EZStrobe.html>; Martinez, 1998b). Built in MS Visio, it is an add-on that uses STROBOSCOPE's simulation engine. The simulation process in EZStrobe starts with using custom drag-and-drop graphics and does not require any programming.

An EZstrobe model is entirely represented as a graphical network, as shown in Figure 6.10, with its nodes and links built using drag-and-drop graphics from EZStrobe Stencil (<http://www.cem.umich.edu/Ioannou/strobosys/ezstrobe/ezstrobe.htm>).

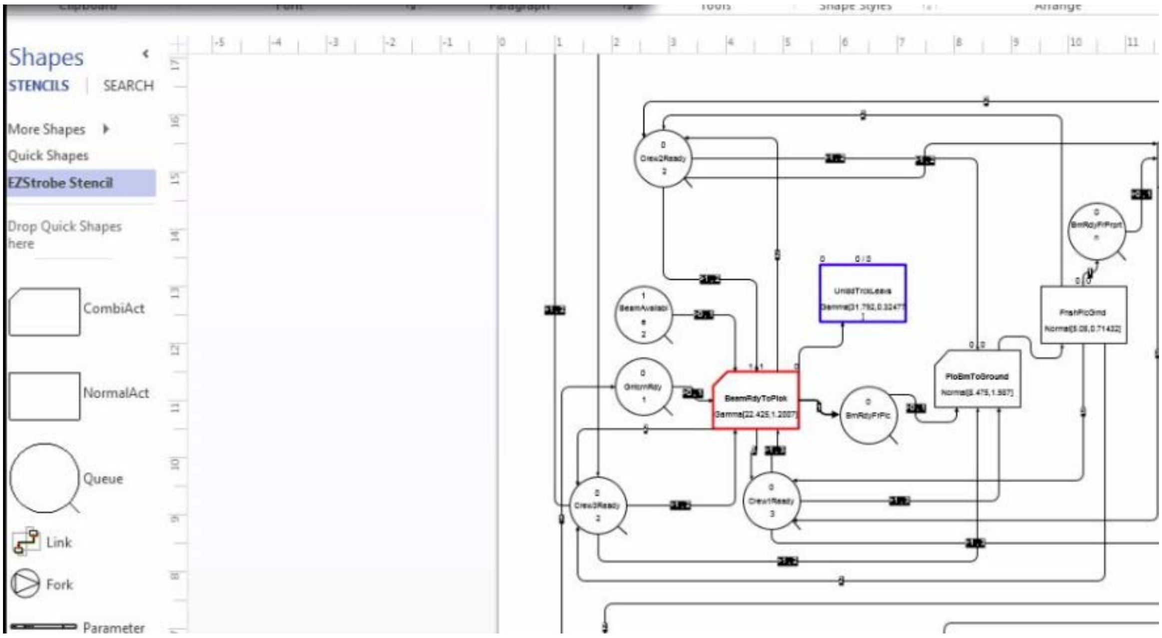


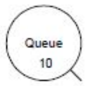
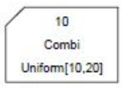
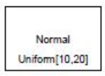
Figure 6.10 EZStrobe modelling elements and graphical network

The complete logic of an EZStrobe model is represented entirely by the activity cycle diagram (ACD) (MacDonald & Gunn, 2012), where all links are annotated to show the start-up conditions for activities and the routing of resources.

The "Stencils", presented at the left side of Figure 6.10, are called EZStrobe modelling elements and are described by Martinez (1998b) and Martinez (2001). Descriptions of the modelling elements presented by Martinez are summarised in Table 6.3. Among these elements, "Fork", "Parameter" and "Link", in particular, were introduced (Martinez, 1998b) to make EZStrobe a powerful decision-making support (DMS) tool. Therefore, the current study selected these elements to explore the capabilities of

EZStrobe (see Sections 7.3.1 and 7.3.4). Furthermore, the exploration phase of the current study included other advanced features of EZStrobe, such as customising output, defining model behaviour dependent on the dynamic model state, and animation of running models for model verification (Martinez, 1998b, 2001).

Table 6.3 Basic elements of EZStrobe program

Name	Symbol	Description
Queue		A Queue is an element that comprises some instances that are holding idle resources. Some of the resources placed in Queues are those released by the termination of instances of preceding Activities. These resources are removed from Queues by the starting instances of succeeding Conditional Activities (Combis).
Combi		A Combi is an element that represents tasks that can start whenever the resources available in the Queues that precede it are sufficient to support the task.
Normal Activity (Bound Activity)		A Normal Activity is an element that represents tasks that start whenever an instance of any preceding Activity ends.
Fork		A Fork is a probabilistic routing element. When the instance of a preceding Activity finishes, the Fork chooses one of its successors. Note: The relative likelihood that a particular successor will be chosen depends on the "P" property of the Branch Link that emanates from the Fork towards the successor.
Link		A Draw Link connects a Queue to a Combi. It shows two pieces of information separated by a comma. The first part is the condition necessary for the successor Combi to start as a function of the content of the predecessor

		Queue. The second part is the amount of resource that the Combi will attempt to remove from the predecessor Queue in the event that the Combi does start. The Combi may not be able to remove the amount attempted if that amount is greater than the content of the Queue, in which case the entire content is removed.
Branch		A Branch Link connects a Fork to any other node except a Combi.

As MS Visio was used as the basis for the EZStrobe design, this allows the user to develop and run the model in MS Visio. EZStrobe creates the equivalent model using STROBOSCOPE statements and sends it to the STROBOSCOPE engine to perform the simulation. The automation is hidden from the user. However, learning and using EZStrobe does not require any knowledge or use of STROBOSCOPE directly. The results of EZStrobe simulation, which can be saved as a .pdf file, are shown in STROBOSCOPE's output window. Moreover, in MS Visio, by right-clicking on each node, the results can be reviewed.

As shown in Figure 6.11, the results are presented in the report sheet. Two main sections of the report present the results on Queues and Activities at SimTime (the time when the simulation calculates the statistics report [Figure 6.11, Number 3]).

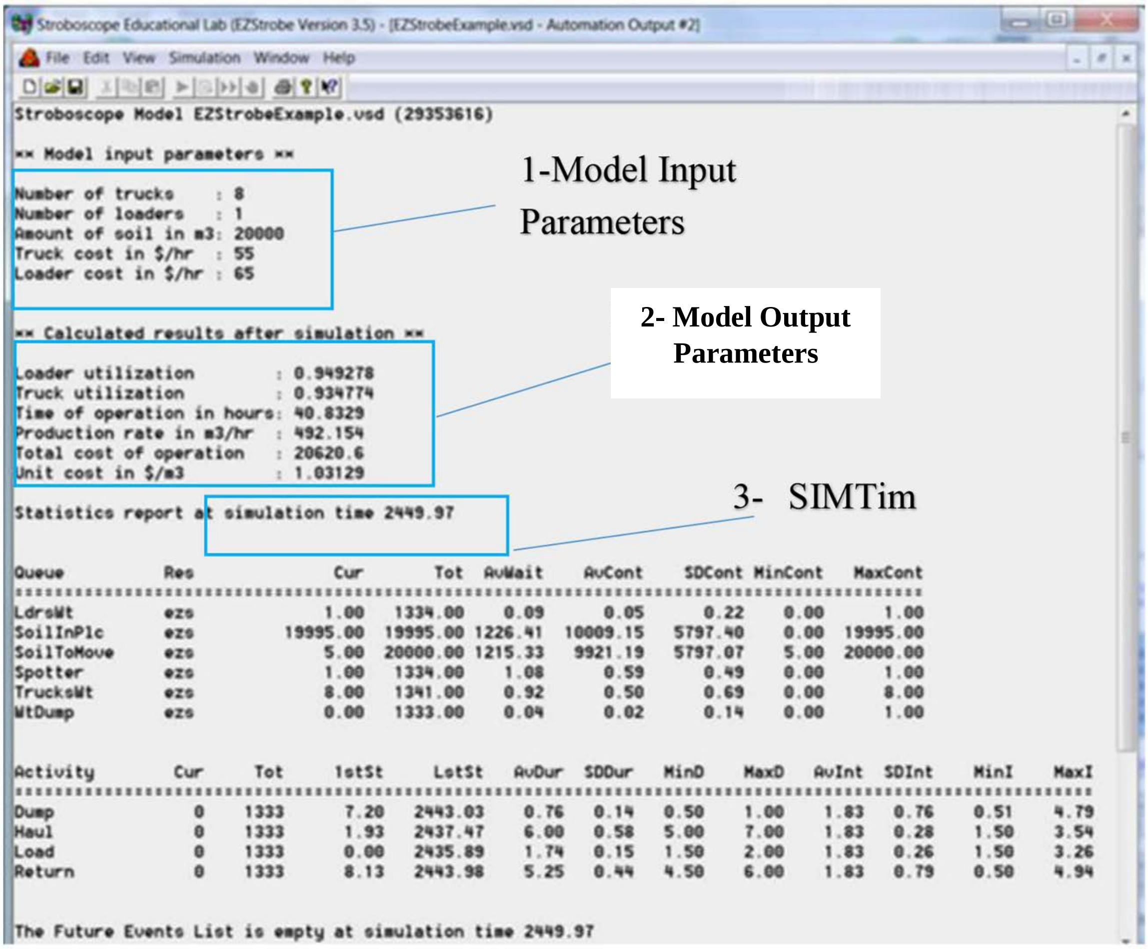


Figure 6.11 EZStrobe report sheet

Depending on the development procedure, the report sheet may or may not include the first two sections presented in Figure 6.11. If the model is developed by parameterising (Figure 6.11, Number 1) and customising the output capability of EZStrobe (Figure 6.11, Number 2), the model input parameters and summary of the calculated results would be presented at the top of the report sheet.

Table 6.4 and Table 6.5 describe the results calculated for Queues and Activities with these presented with different column headers.

Table 6.4 Interpretation of simulation output for Queues

Column header	Description
Res	Shown as “ezs” which means the outputs come from EZStrobe!
Cur	Amount of content at time of the report
Tot	Total amount of resources to ever enter the Queues
AvWait	Average waiting time
AvCont	Time-weighted average content
SDCont	Time-weighted standard deviation of the content indicating the variability of the content
MinCont	Minimum content
MaxCont	Maximum content

Table 6.5 Interpretation of simulation output for Activities

Column header	Description
Cur	Current number of times that Activity is being performed at time of report
Tot	Total number of items started
1stSt	Time at which first instance started
LstSt	Time at which last instance started
AvDur	Average duration
SDDur	Standard deviation of duration
MinD	Minimum duration
MaxD	Maximum duration
AvInt	Average time between successive starts
SDInt	Standard deviation of time between successive starts
MinI	Minimum time between successive starts
MaxI	Maximum time between successive starts

In the model development, the following points would need to be taken into account (Martinez, 2001) to build a model in accordance with the logic of the program, and to consequently run a STROBOSCOPE simulation to achieve the outcomes:

1- A Queue can follow any other node except another Queue.

2- A Queue can only precede a Conditional Activity (Combi).

3- Combis can only follow Queues, but can precede any other node except for a Combi.

4- A Normal Activity can follow any node except a Queue, and can precede any node except a Combi.

In running a simulation, a modeller can receive the following two types of messages on the EZStrobe window:

1- The message prompted by STROBOSCOPE:

1-1 The message indicates SimTime and the end of the simulation run due to “Lack of resources”, or

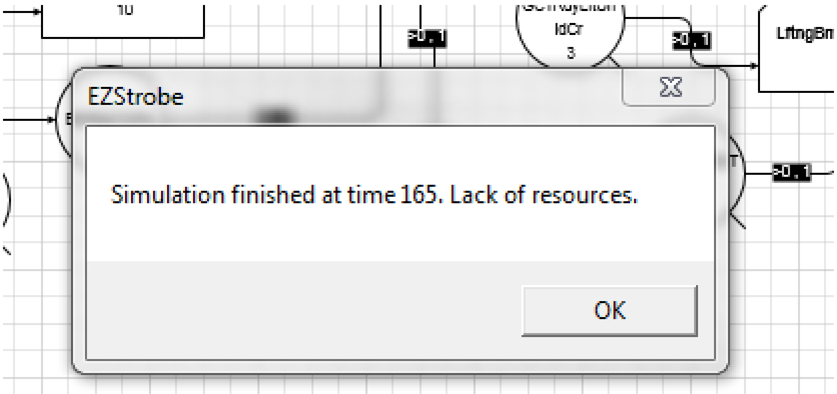


Figure 6.12 EZStrobe message at SimTime

1-2 The message “Simulation finished at 100000. Time limit reached!” shows that the model includes an unlimited cycle and is not able to stop.

Several simulation systems have even been designed specifically for construction (e.g. Halpin & Riggs, 1992; Martinez, 1996) but, in comparison to EZStrobe, these systems could not meet the need for a very easy-to-learn and simple environment to minimise the effort required in modelling (Martinez, 2001).

As presented in the literature review (subsection 3.1.2.4), EZStrobe employs a three-phase activity scanning (AS) approach to represent the model through a network called an activity cycle diagram (ACD) (MacDonald & Gunn, 2012). Generally, activity scanning (AS) models are developed based on the different activities that can take place in an operation. Therefore, a modeller is required to focus on identifying activities, the conditions required for the completion of activities and the outcomes of the activities (Martinez, 2001).

Modellers can more easily simulate an operation through an ACD network by using the "Stencils" in EZStrobe, designed for this purpose. The important role played by the ACD is as a guide for using a simulation programming language to code the model. In the next section, the current study reviews and present EZstrobe's ACDs and modelling procedure.

6.3 MODELLING PROCEDURE

According to Halpin and Riggs (1992), the modelling elements included in a simulation program can be used in a variety of patterns to model construction operation structures. Halpin and Riggs (1992) also emphasise the identification of the major resources involved in the operation, as well as establishing the various states through which the resources traverse in their work assignment paths and cycles. The integration of the resource paths and cycles are fundamental in building the basic structure of the operation.

Therefore, the current research study reviewed other research studies, specifically conducted in the construction simulation context (e.g. Martinez, 1998a, 2001; Marzouk et al., 2007; Marzouk et al., 2008; Marzouk et al., 2006), and found that the main steps used by these studies in their simulation experiments were as follows:

1- Defining Queues, Activities and conditions needed to start an Activity, and the outcome of the Activity

2- Identifying and assigning the content of each Queue

3- Identifying the type of link that needs to be drawn to connect Queues and Activities

4- Assigning annotations to the link:

4-1 Drawing a link to connect Queue to Activity: therefore, the annotation indicates the required conditions for an Activity to start. According to EZStrobe, it should be noted that if the link connects Combi and Queue, then the annotation includes one more section to present how many units will be released (if possible) from the connected Queue

4-2 Drawing a link to connect Activity to any node: therefore, the annotation represents the amount of resource that will be released through the link each time an instance of the predecessor Activity ends

5- Estimating the duration of each Activity:

5-1 Using a uniform distribution sample to estimate the duration of Combi

5-2 Using a probability distribution sample to estimate the duration of Normal Activity

6- Creating a “Probabilistic Branch” to connect the Fork to any node except Combi: in this way, the developer determines the route that needs to be followed for each condition

7- Parameterising the models: the “Parameters” option in EZStrobe allows the designer/developer to assign a symbolic name and description to these values. The “Model parameters” page can represent the amount of materials (resources) to be moved, the number of machines to be used, the hourly cost of equipment/machines and other indirect cost parameters. It should be noted that using the “Parameters” option allows the developer to create generic models that adapt to a wide range of similar operations, with these models able to be used later by specifying the appropriate parameter value

8- Customising output: this step can be accomplished using the “Results” option provided in EZStrobe. This option allows the modeller to define the formulas to measure the performance of the associated parameters, with these parameters entered in the previous step.

The current study starts by identifying and collecting the data required for the completion of the aforementioned steps. This is the first and most important task before developing an ACD and simulating an operation. Therefore, the next section describes the required data and the methods used for their collection in this research study.

6.4 COLLECTING THE REQUIRED DATA

As mentioned, to develop a simulation model, the required data should first be identified, and then the conceptual model should be built upon the collected data (Halpin & Riggs, 1992). Reviewing the above steps for modelling a given operation, the current research study identified that the required data could relate to the following information:

1- Identifying work tasks
2- Duration of tasks
3- Sequences of performance accomplishment
4- Resources

5- Logic of resource utilisation
6- Identifying the state of resources
7- Incidents/reasons for non-completion
8- Identifying interactions among resources
9- How and why new decisions should be made at the site

As explained in the research methodology chapter (Chapter 5, Section 5.4.2), the following methods have been selected for data collection in the current research:

1- Documentation, which includes analysis of the extant documents and field note taking during site visits, and
2- Participant observation.

In the matrix (in Table 6.6), the relationship between the methods for data collection and those nine data sets listed on the previous page are presented.

Table 6.6 Methods used in collection of required data in current study

Data set Number	Descriptions of required data	Document analysis	Note taking		Observation
			Meetings	At site	
1	Identifying work tasks	√		√	√
2	Duration of tasks			√	√
3	Sequences of performance accomplishment	√		√	√
4	Resources	√		√	√
5	Logic of resource utilisation	√		√	√
6	Identifying the state of resources			√	√
7	Incidents/reasons for non-completion	√	√	√	√
8	Identifying interaction among resources			√	√
9	How and why new decisions should be made at the site			√	

In this research, as previously mentioned, the particular operation to be simulated is the gantry launching operation (for the Great North Road Interchange [GNRI]) which involves the delivery and installation of precast super T-beams for the construction of four ramps, as discussed in Section 6.1. In this operation, a relatively new construction technique, called the gantry launching operation, was utilised. This technique had no solid work breakdown structure (WBS) nor was there a conceptual framework. Therefore, at the initial step, the study started data collection using analysis of the extant and relevant documents to gain a better understanding about the operation/system behaviour).

Identification of the complete details for these data sets did not happen at the initial step. The study had to wait for the operation's commencement so the method by which its execution was accomplished could be observed during fieldwork. Therefore, at the early stages of this fieldwork study, the availability of some data could allow the research study to develop an initial conceptual model. The next section explains the approach undertaken for the development of this model.

6.5 DEVELOPING AN INITIAL CONCEPTUAL MODEL

As there is no specific modelling procedure for the implementation of EZStrobe, the study undertook a preliminary study to determine how the steps recommended by previous studies could be applicable to the current research. In addition, it was necessary to understand the operation behaviour by developing an initial conceptual model.

At the preliminary stage, through document analysis, the research sought to collect the valuable information presented in Table 6.7. The study then began to formulate a WBS for the operation indicating the sequences of tasks, and interdependencies between tasks and resources, as well as the states of resources. The study divided the entire work into discernible categories: preliminary works, temporary works, main operations, ancillary works, activities and resources as shown in the second column in Table 6.7. These small chunks were then broken down and denoted as presented in the table. Finally, through using simple flow chart elements, such as rectangles, diamonds and arrows, the first working model was developed (see Figure 6.13).

Table 6.7 Data required for initial model conceptualisation

Data set number	Data	Description	Annotation
1	Preliminary Works	Gantry plinth	P1
		Gantry assembly	P2
1	Temporary Works	Temporary works required to be done before commencement of each span and that stay for the whole span completion	TW

Data set number	Data	Description	Annotation
		Installation of runway beams	T1
		Installation of access platform	T2
		Temporary works required to be done before commencement of each span and that need to be repeated for each beam	TWB
1	Main Operations	Preparation for delivery of super T-beam	Op.1
		Delivery	Op.2
		Placing the super T-beam	Op.3
		Preparation of gantry for next round	Op.4
1	Ancillary Works	Preparation of beam (included stranding stress bars and temporary walking timber on top of beam)	An.1
		Lock master winch	An.2
		Lock anchor rope	An.3
		Unlock master winch	An.4
		Unlock anchor rope	An.5
1	Activities	Moving:	Ac.2-1
		• Loaded truck moves back toward gantry truss	M1
		• Truss/slave winches move forward to top of the truck	M2
		• Truss moving down	M3
		• Unloaded truck moves to leave gantry area/ site	M4
		• Truss moving down to put beam on ground	M5
		• Move gantry truss forward	M6
		• Move gantry truss forward to centre over first span	M7
		Lift	Ac.2-2
		Launch:	Ac.2-3
		• Launch super T-beam one span forward	L1
		• Launch super T-beam forward to the first/next span	L2
		Temporary placement	Ac.3-T
		Side shifting	Ac.3-S
		Permanent placement	Ac.3-P
4	Main Resources	Trailer and jinker	T
		Gantry crane	G
		Super T-beam	B
4	Other Resources	Lifter, Merlo, Tandano crane, cherry picker, auxiliary support, erection beam support, bogie, rollers, master and slave winches	
4	Types of Beam	(I) Edge beam, (II) Intermediate beam	

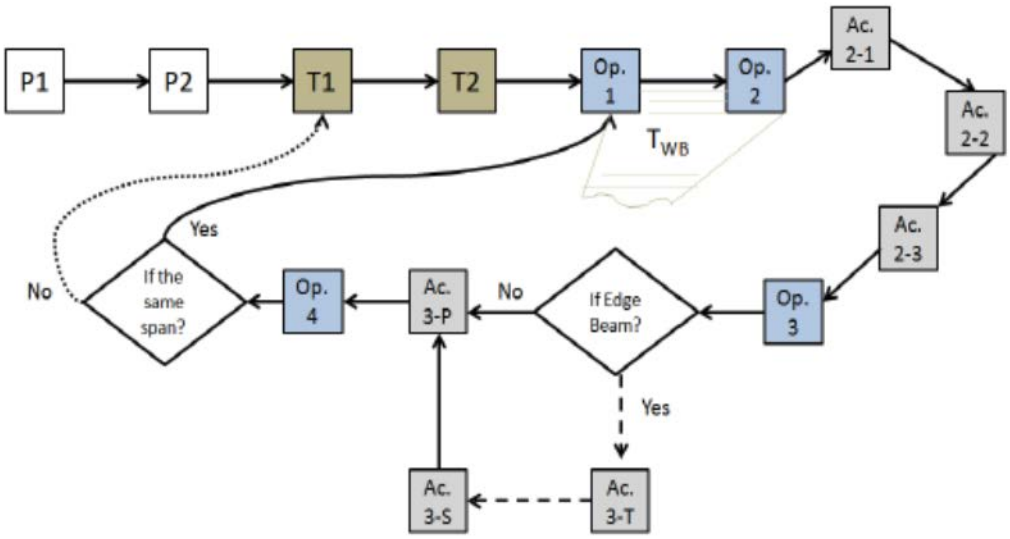


Figure 6.13 Initial conceptual model of bridge construction project using launching girder

As shown in Figure 6.13, the project starts with preliminary works which comprise preparatory work on the gantry plinth and gantry assembly (shown as P1 and P2), with this followed by two temporary work activities denoted as T1 and T2. Consequently, the work section that forms the major focus of the current study is ‘Operations’. The operations begin with Op.1 and work through to Op.4. With the completion of Op.2 and its relevant activities, the next part of the process is performing the placement operation for the bridge girders (T-beams). Depending on the type of beams being placed (intermediate or edge beams), a decision would need to be made on the direction of the workflow. In fact, the first decision affecting the position of the beams would be whether it is an edge or an intermediate beam. Finally, when the placement is done and the beams are positioned, Op.4 is then undertaken, with its finalisation calling for new decisions. For instance, if the operation continues in the same span, then the next cycle will start from Op.1. However, if the operation is going toward the completion of the next span, then the cycle will begin with the accomplishment of T1 on the next pier.

Further analysis continued on the system behaviour when the gantry launching operation (for the GNRI) started, with the preliminary study trying to identify the different states held by a resource in the process. According to Halpin and Riggs (1992), in the initial modelling phase, all possible idle and active states of the resources should be identified and taken into account, as the idleness of some resources could be conditional on the availability of other resources. Therefore, the second conceptual model presented in

Figure 6.14 was developed to show the interactions between resources and their states in different levels within Op.2.

From Figure 6.14, it can be observed that four main categories of work are involved in Op.2: “Delivery”, “Lifting”, “Ancillary works” and “Moving”. In the “Delivery” phase, trucks and jinkers transport the super T-beams to the site from the casting yard. The trucks manoeuvre to platforms where the gantry crane lifts the super T-beams. This is the “Lifting” phase within the conceptual framework. The next phase involves the movement of the super T-beams to place them in their respective positions along the bridge. The “Ancillary works” must be completed before the final placement of these beams, with the type of ancillary works depending on whether the beams are intermediate or edge beams. These ancillary works include preparation of the beam, locking of the master/slave winch, etc. as indicated in Table 6.7. When the beams are fully in position, Op.2 is completed, and the performance of the work shifts to the next operation (Op.3).

To analyse and present the states of the resources involved in the above operation, in line with Halpin and Riggs (1992), the current study focused on the major resources. The study could then establish the various states of the three major resources: the twin-truss gantry, the truck and the super T-beams to develop the skeletal framework of Op.2. The states of the resources used for the completion of each activity were represented using traffic light symbols, with “Red” representing an idle state; “Green” representing an active state; and “Amber” representing a fusion state. For example, at the lifting phase when cranes attached to the twin-truss gantry lift a super T-beam, the truck is in an idle state and, thus, a Red dot depicts this state. However, at this phase, the twin-truss gantry and the super T-beam are both in active states; hence, two Green dots show their states in Figure 6.14 below.

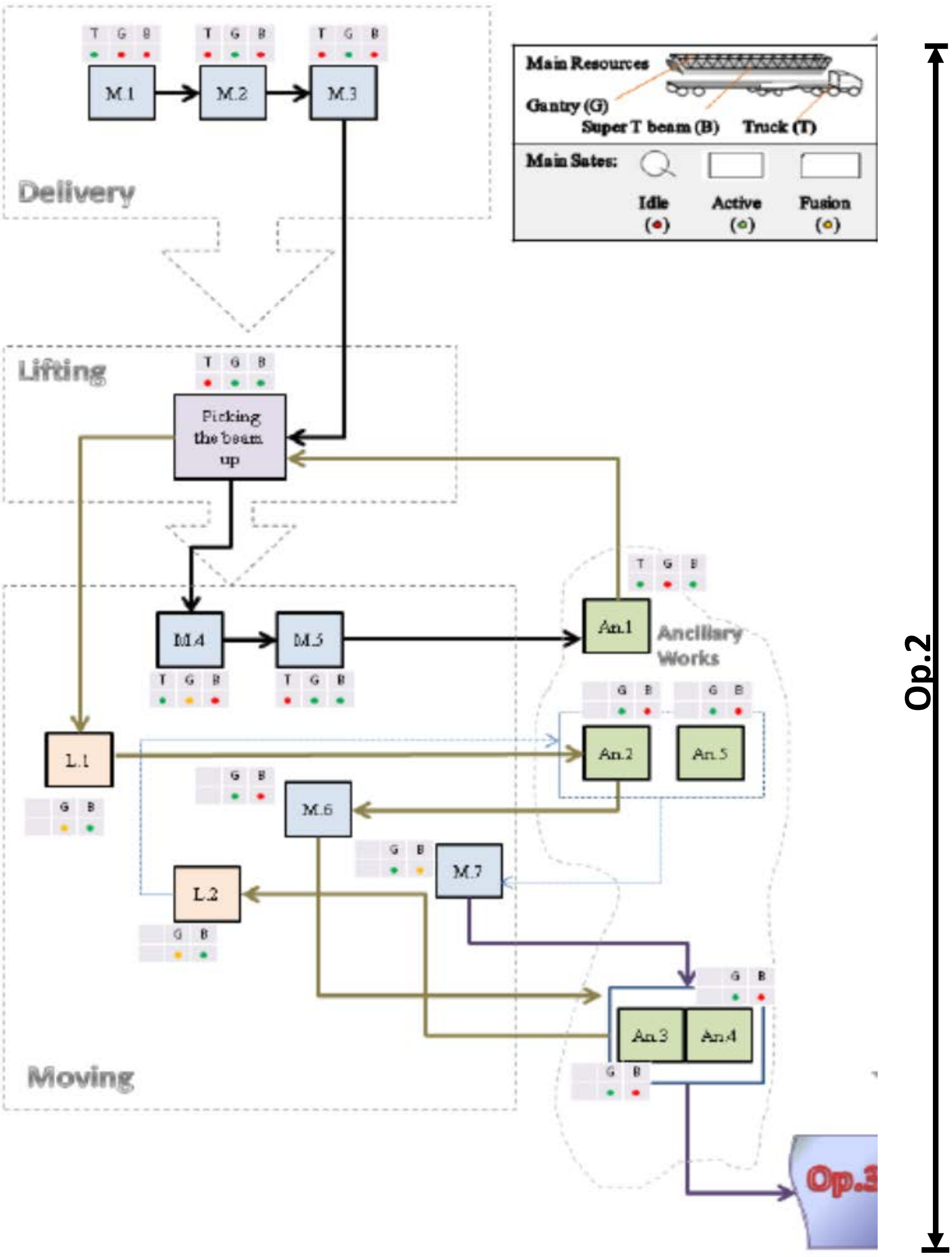


Figure 6.14 Enhancing level of detail in conceptual model using traffic light symbols

With the researcher having gained an understanding of the system behaviour by this stage, the research started to proceed towards the simulating procedure, as previously discussed in Section 6.3. Firstly, the study sought to translate the developed conceptual model above into EZStrobe language. The next section explains modifying the model and completion of the simulation procedure steps.

6.6 MODIFYING THE CONCEPTUAL MODEL IN ACCORDANCE WITH EZSTROBE STANDARDS

6.6.1 SIMULATING PROCEDURE: STEP 1

At this stage, the current research, in line with the first step of the simulating procedure (see Section 6.3), sought to translate the insight gained on system behaviour through the initial conceptual model into the ACD model. Therefore, the study first needed to sort out the information related to the activities, their required conditions and their outcomes, as recommended by Martinez (2001).

Table 6.8 Information required to build ACD model

Conditions needed to start	Activity	Outcome of activity
Loaded truck idle at site Empty **g**antry **c**rane waiting to load	Beam delivery in gantry area	- gantry crane ready to load - truck ready to haul - super T-beam idle
Loaded **g**antry **c**rane ready to move down Unloaded **t**ruck ready to **h**aul	Moving the beam down to undertake preparation (including stranding the stress bars and timbering works over the beam)	- super T-beam idle on the ground (ready for preparation) - unloaded gantry crane idle
Empty **g**antry waiting to **l**oad Super T-beam **r**eady to **l**ift	Lifting the super T-beam	- super T-beam idle on the gantry crane - loaded gantry idle
Loaded **g**antry ready to move forward Super T-beam idle	Launching the gantry forward	- loaded gantry ready to deliver beam to the desired place - super T-beam ready to be placed
Loaded **g**antry idle on the top of the span Supports ready for beam placement Super T-beam ready to be placed	Placing the super T-beam	- unloaded gantry idle - super T-beam ready to be fixed on the supports
Unloaded **g**antry idle	Preparation of the gantry for next round	- gantry crane ready to load - truck ready to haul - super T-beam idle

The study captured the information included in Table 6.8 to create the layout for the ACD model (see Figure 6.15).

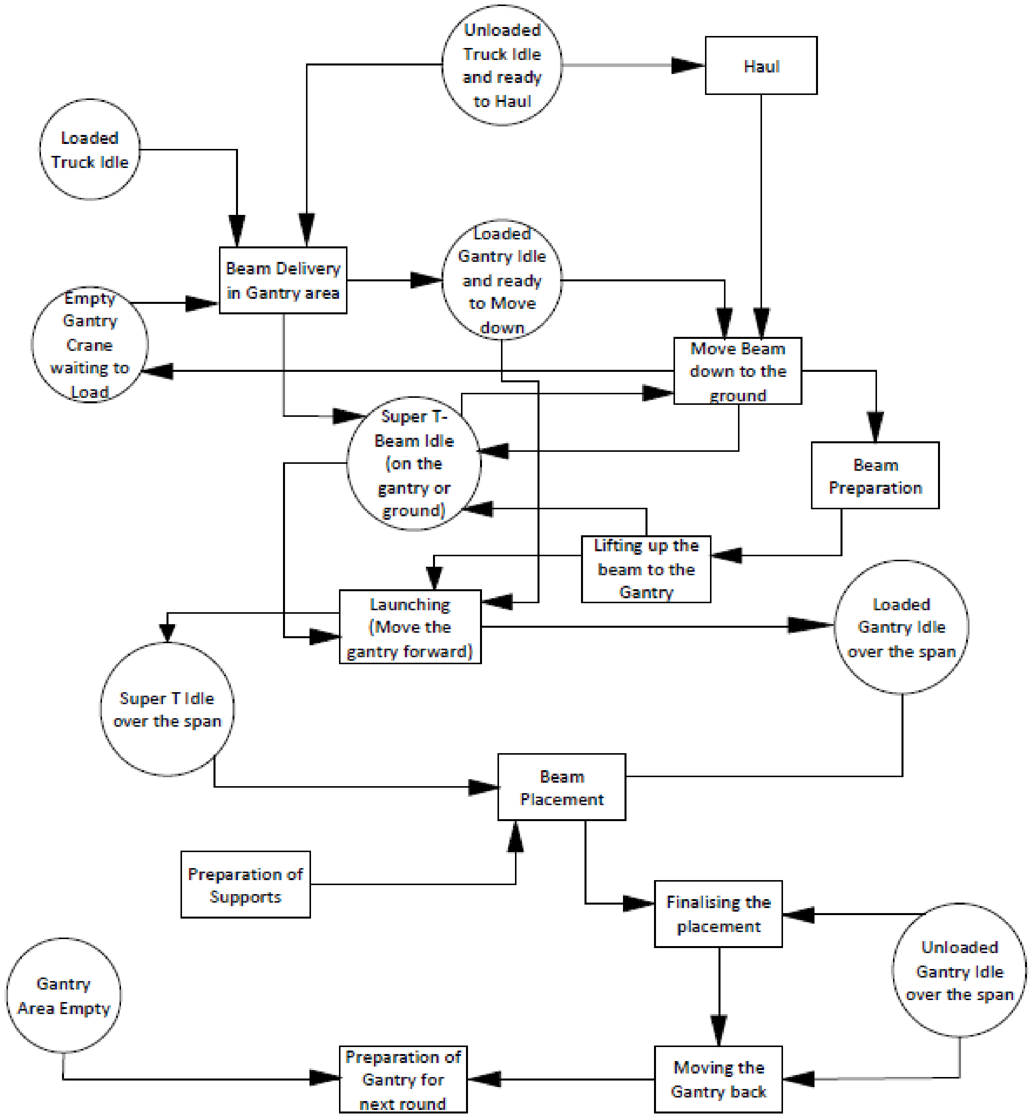


Figure 6.15 ACD model for beam delivery operation using launching gantry

The ACD model in Figure 6.15 illustrates the sequence of activities and the way that an activity receives its required resource(s). A square and a circle in the model represent the states of the resources to enable a clearer expression of the concepts of the operation.

As the model shows, the objective of the studied operation is the installation of precast super T-beams between bridge spans. Trucks deliver the super T-beams to the loading area from where the gantry crane picks up the beams. The gantry crane then lifts the beams (whether intermediate or edge) to their placement points.

With the standard elements of the EZStrobe program applied, this led to modification of the developed ACD model, which thus became the new version presented in Figure 6.16.

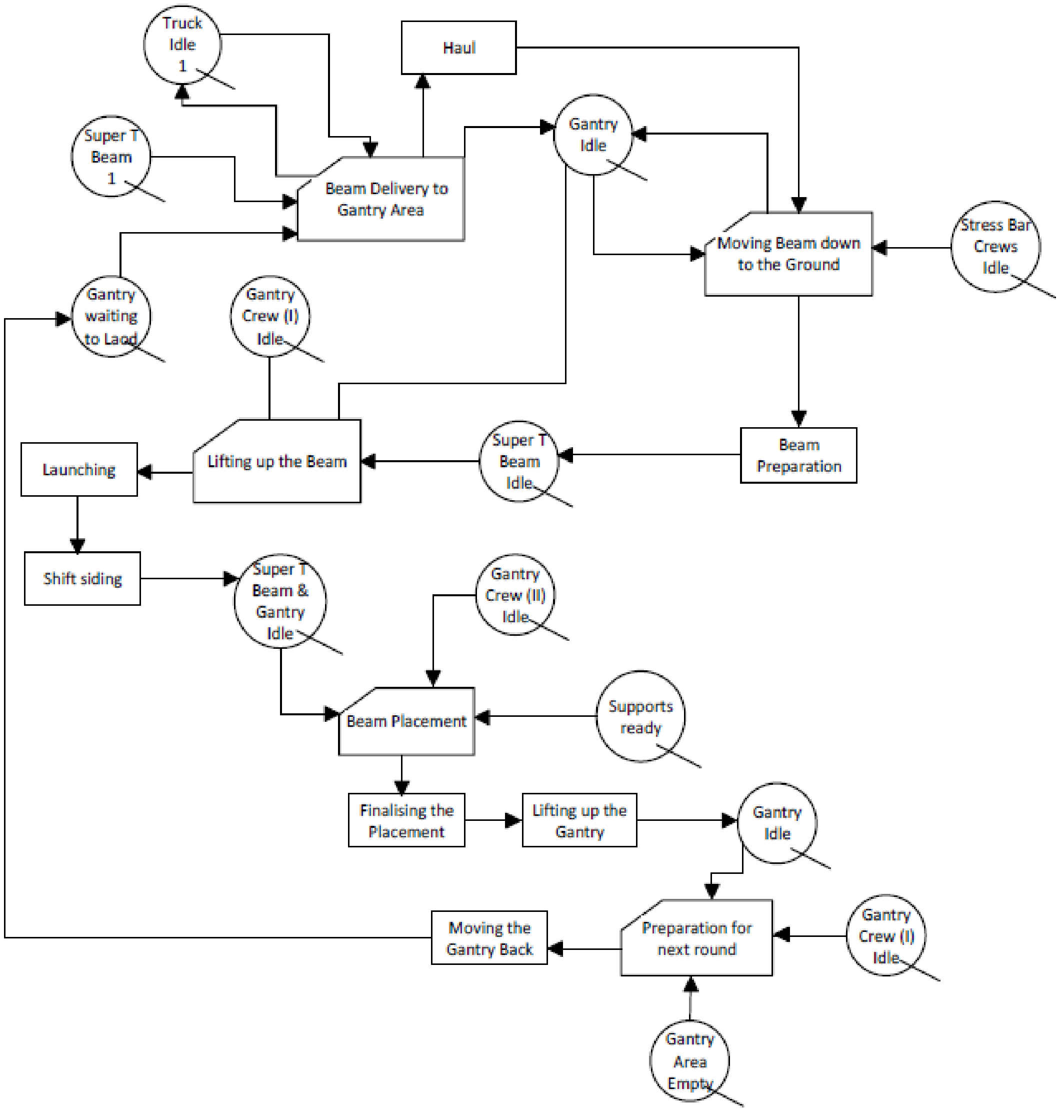


Figure 6.16 EZStrobe ACD model for beam delivery operation using launching gantry

In order to complete the next step in the simulation procedure, the research study found that further data were required. The data collected through field note taking and observation, and the steps which used the data, are discussed in the following sections.

With the study's aim being to develop a framework for simulating a particular operation, while aligning this with an exploration of the capabilities of EZStrobe, the rest of the simulation procedure's steps were achieved by using the data collected during the construction of the first span (Span 7/Ramp 1) in this preliminary phase.

6.6.2 SIMULATING PROCEDURE: STEP 2

In Step 2, each Queue's content was identified and assigned. The data were collected from observations and note taking from the fieldwork. Table 6.9 presents the information (i.e. data) collected on the human resources content.

Table 6.9 Information on human resources content

Gantry Crew (Queue)	Number of Persons (Queue's Content)
GC1	3
GC2	4
GC3	4

As shown on Table 6.9, the gantry launching operation (for the GNRI) involved three crews (GC1 to GC3). Table 6.10 describes their assigned jobs in more detail.

6.6.3 SIMULATING PROCEDURE: STEPS 3 AND 4

In Step 3, the modeller should identify the types of link between Queues and Activities, with an analysis conducted of the interdependencies between different elements included in the model. This analysis can present the sequence of the Activities' completion as well as the conditions required for the commencement of Activities. Then, in Step 4, an analysis of these interactions identifies and presents the amount of resources' flow between the Activity and the Queue.

Furthermore, entering the model elements into the EZStrobe environment showed that, to be acceptable to EZStrobe, all elements should be given names without spaces between the names. Moreover, the review of previous EZStrobe models showed that the name used for Activities (either Normal or Combi), and Queues should imply their roles and responsibilities. With the completion of Steps 3 and 4, after tabulating the information, the details are presented in the following tables (Tables 6.10-6.11).

6.6.4 SIMULATING PROCEDURE: STEP 5

Step 5 estimates the duration for the completion of each Activity, with EZStrobe using "Sampling Function" for distribution analysis, for this purpose. To complete this step, durations for all Activities should be collected in fieldwork and then analysed using the probability distribution function (PDF) (see Chapter 5, Section 5.6). When modelling each Activity in EZStrobe, the duration box presents two options:

1- entering the duration of the Activity without the "Sampling Function", and
2- assigning the distribution function by clicking the key next to the duration box (see Figure 6.17)

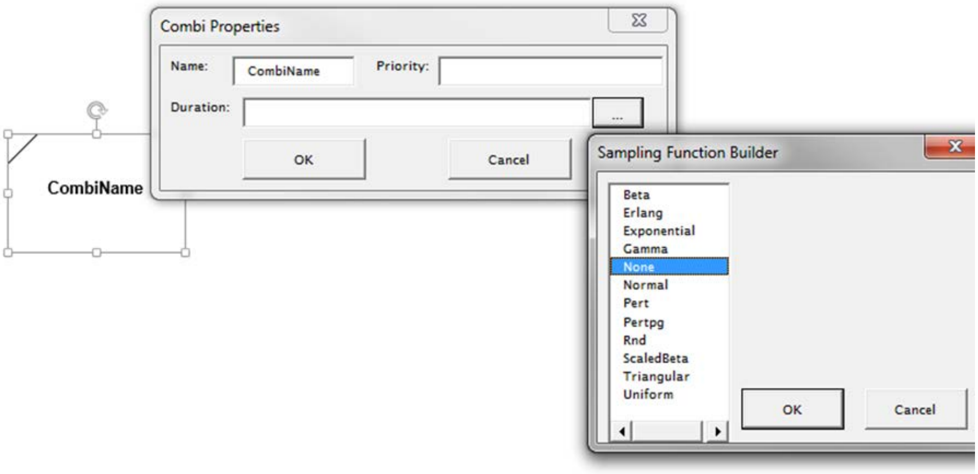


Figure 6.17 "Sampling Function Builder" in EZStrobe

Due to the lack of data in the initial EZStrobe model of Span 7, the first option was used to enter each Activity's duration. In this way, the duration of Activities involved in the delivery and placement of the first beam of Span 7 was entered into the model (see Table 6.10). Later, as explained in Section 7.1.3., when the data on the beam placement operations in Span 7 were completed, the study used PDF analysis so it could explore the "Sampling Function" capability of EZStrobe.

Table 6.10 Information on process Activities, their sequences and durations

Sequence of completion of Activities	Activities	ACD model annotation	Duration (minutes)	Start time
1	Beam Delivery to Gantry Crane	BmDlvryToGCrne	30	0
2	Unloaded Truck Ready to Haul	UnlddTrckRdyToH	10	30
3	Beam Placement for Preparation on the Ground	BmPlcmntFrPrprt	10	40
4	Preparation Beam on the Ground	PrprtnOfBmOnGrn	15	50
5	Lifting the Beam up to the Crane (from the Ground)	LftngBmUpToCrn	15	65
6	Prepared Beam Ready to Load	PrprdBmRdyToLd	15	80
7	Beam Launching to Span 7	BmLnchToSpn7	30	95

Sequence of completion of Activities	Activities	ACD model annotation	Duration (minutes)	Start time
8	Loaded Crane Stops above Span 7	LddCrnStpSpn7	10	125
9	Beam Placement on its Support	BmPlcmntOnSuprt	20	135
10	Moving the Unloaded Crane above Span 7	MvngUpUnldCrn	20	155
11	Unloaded Crane Stops above Span 7	UnldCrnStpSpn7	10	175
12	Returning Unloaded Crane to Auxiliary Support	RtrnUnldCrnToAS	30	185
13	Unloaded Crane Locked	UnlddCrnLock	15	215
			230 minutes	

Table 6.11 Information on resources and Queues

Types of Resource	Resources	ACD model annotation according to Queue's state	Description of the annotation	Maximum Content
Human Resources (Gantry Crew)	Gantry Crew 1 (GC1)	GC1RdyToPckBm	Gantry Crew 1 is Ready to Pick Up the Beam from the Loaded Truck which is already stopped under the Gantry Crane	3
		GC1RdyToMvLdCrD	GC1 is Ready to Move the Loaded Crane Down	
		GC1Idle	GC1 is in Idle state	
		GC1RdyLftUnldCr	GC1 is Ready to Lift Up the Unloaded Crane	
		GC1RdyToPshCrn	GC1 is Ready to Push the Crane toward Span 7	
		GC1RdyToMvCrD	GC1 is Ready to Move the Crane Down (to Deliver the Beam to its Supports)	
		GC1RTLftUpUnldC	GC1 is Ready to Lift Up the Unloaded Crane (after delivering the beam to its supports, the unloaded crane should be lifted up)	
		GC1WtfrGC23	GC1 Waits for GC2 and GC3 to complete the Placement of the Beam on its Supports: either Temporary or Permanent Placement	

Types of Resource	Resources	ACD model annotation according to Queue's state	Description of the annotation	Maximum Content
	Gantry Crew 2 (GC2)	GC2WtFrCrnPBm	GC2 Waits for Crane to Place the Beam on the Ground	4
		GC2RdyToPrpartn	GC2 Ready for Preparing the Beam after its Placement on the Ground	
		GC2WtFrLftBmUp	GC2 Waits to Lift Up the Beam (after the beam is placed on the ground, GC2 prepares the beam for launching to the span. Then, during the time that GC1 handles lifting up the prepared beam, GC2 waits for a while before handling the launching)	
		GC2RdyToPshBm	GC2 is Ready to Push the Beam toward Span 7	
		GC2RdyToRtrnCrn	GC2 is Ready to Return the Unloaded Crane to where it should be Locked	
	Gantry Crew 3 (GC3)	GC3RdyInSuprts	GC3 is Ready in the Supports to process the Placement of the Beam	4
		GC3RdyToFinlzP	GC3 is Ready to Finalise the Placement	
	Combined Crews	GC12RdyRtrnCrn	Both GC1 and GC2 are Ready to Return the Crane while GC3 is working on Placement of the Beam	7
		GC23RdyToPlcBm	GC2 and GC3 are Ready to Place the Beam Down onto its Supports	8
Equipment	Crane	GntryCrneRdyToL	Gantry Crane is Ready to Load the Beam which has been Delivered by Truck	1
		LddCrneRdyToMvD	Loaded Crane is Ready to Move Down to place the Beam on the Ground	
		UnldCrnRdyToLBm	Unloaded Crane is Ready to Load the Beam	
		LddCrnRdyToPsh	Loaded Crane is Ready for Launch to Span 7	
	Truck	LddTrckIdle	Loaded Truck is Idle	1
Materials	Beam	BmRdyToLftUp	Beam is Ready to be Lifted Up to the Crane. (When the beam is delivered to the gantry area by truck, some steps should be accomplished to make the beam ready for hanging from the crane)	1
		BmRdyToPlc	Beam is Ready for Placement on the Ground	

Types of Resource	Resources	ACD model annotation according to Queue's state	Description of the annotation	Maximum Content
		BmRdyFrPreprtn	Beam is Ready on the Ground to be Prepared for Launching Operation	
		PrprdBmRdyToP	Prepared Beam is Ready to be Pushed Forward to Span 7	

6.7 INITIAL SIMULATION OF STUDIED OPERATION AT PRELIMINARY PHASE

The information presented in Table 6.10 and Table 6.11 was used to develop the EZStrobe model for the construction of Span 7/Ramp 1. The resulting model was developed, as presented in Figure 6.18.

Modelling is successful when the simulated model accurately reflects the workflow process as executed in the real-world project (Nikakhtar et al., 2011, p. 202). Therefore, before any further analysis is conducted, the model is verified and evaluated by inspecting its logic. Model validation helps to construct a credible simulation model (Nikakhtar et al., 2011).

The current research study added the verification and validation steps between the other steps (as explained in Section 6.3), and the next section discusses the associated details.

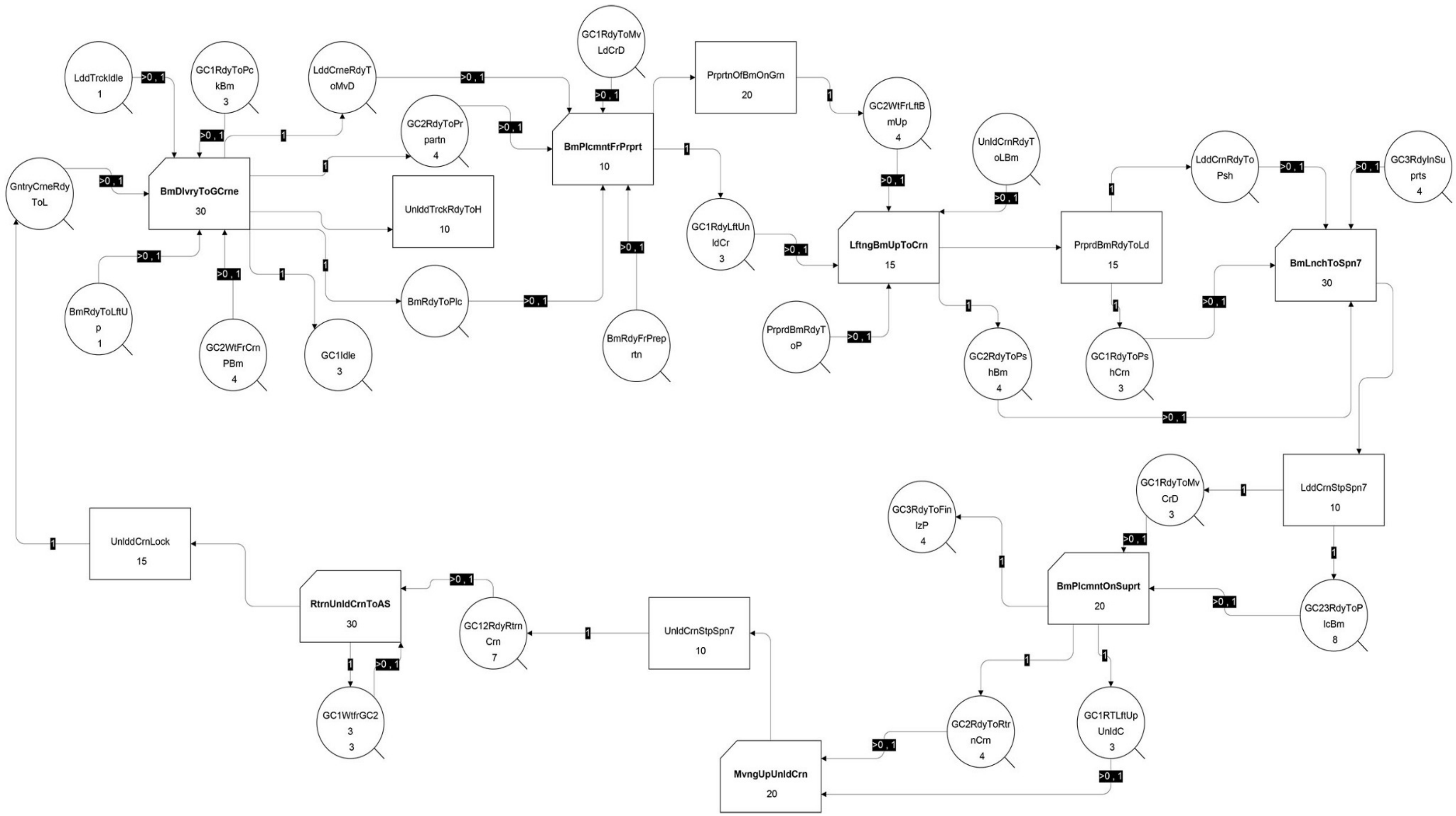


Figure 6.18 Initial developed simulated model on Span 7

6.7.1 VERIFICATION AND VALIDATION

Model verification is concerned with comparing the logic of the simulated model with the logic of actual operations (to assess the concept of the developed model). According to Nikakhtar et al. (2011), verification of a simulated model should perform the following steps: inspecting the logic of the developed model, running a simulation, tracing the entities and evaluating the consistency of the model's statistics. Furthermore, in referring to the descriptions of the simulation output, as discussed in Section 6.2, the results for Activities and Queues are understood to depend on the number of instances and operation cycles, and the sequence of task accomplishment and the logic of the use of resources. Therefore, for verification, the study formulated the following assumptions in accordance with the logic of the actual process and the simulation program:

1- Each Activity includes one instance.
2- The model is only for one round of operation, starting with the delivery of the super T-beam by the truck, continuing with the super T-beam's placement on Span 7, and finishing with returning the gantry crane to auxiliary support.
3- The total duration for the completion of one round of operation, as shown in Table 6.10, is 230 minutes.
4- The maximum content of resources is in accordance with the information presented in Table 6.11.
5- The model is based on the collection of durations for the first beam placement operation, with these assigned to the model using the non-probability function.
6- The sequence of performing the Activities according to the real-world scenario is presented in Table 6.10, where:

    6-1 Completion of Activity 1 allows Activity 2 to start; completion of Activity 2 allows Activity 3 to start; with the same conditions applying for Activities 4, 5, 6, 7, 8, 9 and 10
    6-2 When Activity 9 is in progress, Activity 11 can start
    6-3 The start of Activities 12 and 13 is dependent on the completion of Activity 11.

When the EZStrobe simulation was later run, the assumptions were assessed and results were obtained. The next sections first present the output of the simulation: at the same time, verification and validation were continuing by interpreting the simulated model output and undertaking comparison analysis between the logic of the simulated model and the actual process. Furthermore, some of the time-based parameters resulting from the simulation (Tot, AvDur, 1stSt and LstSt), and a content-based factor (Cur) were used for the validation of the model. Output from the group of parameters could help the modeller to compare the cycle time of the operation, while output from the above factor could assist in tracing the amount of the Queues' content that had transited through the process.

6.7.2 MODEL OUTPUT

As previously discussed, the simulation report sheet starts with this statement: "Statistics report at simulation time": in the output of this model, the simulation time (SimTime) is 165.

As shown in Figure 6.19, the report sheet is followed by two tables. The first table includes statistical results on Queues, while the second table presents the results related to Activities.

Stroboscope Model Drawing1 (813348553)

Statistics report at simulation time 165

Queue	Res	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
BmRdyFrPreprtn	ezs	0.00	0.00		0.00	0.00	0.00	0.00
BmRdyToLftUp	ezs	0.00	1.00	45.00	0.27	0.45	0.00	1.00
BmRdyToPlc	ezs	1.00	1.00	90.00	0.55	0.50	0.00	1.00
GC12RdyRtrnCrn	ezs	0.00	13.00	32.31	2.55	2.10	0.00	7.00
GC1Idle	ezs	4.00	4.00	146.25	3.55	0.50	3.00	4.00
GC1RTLftUpUnldC	ezs	0.00	6.00	0.00	0.00	0.00	0.00	3.00
GC1RdyLftUnldCr	ezs	3.00	3.00	165.00	3.00	0.00	3.00	3.00
GC1RdyToMvCrD	ezs	0.00	3.00	0.00	0.00	0.00	0.00	3.00
GC1RdyToMvLdCrD	ezs	0.00	0.00		0.00	0.00	0.00	0.00
GC1RdyToPckBm	ezs	2.00	3.00	125.00	2.27	0.45	2.00	3.00
GC1RdyToPshCrn	ezs	3.00	3.00	165.00	3.00	0.00	3.00	3.00
GC1WtfrGC23	ezs	3.00	16.00	6.56	0.64	1.07	0.00	3.00
GC23RdyToPlcBm	ezs	5.00	8.00	103.13	5.00	0.00	5.00	8.00
GC2RdyToPrpartn	ezs	5.00	5.00	150.00	4.55	0.50	4.00	5.00
GC2RdyToPshBm	ezs	4.00	4.00	165.00	4.00	0.00	4.00	4.00
GC2RdyToRtrnCrn	ezs	1.00	7.00	23.57	1.00	0.00	1.00	4.00
GC2WtFrCrnPBm	ezs	3.00	4.00	135.00	3.27	0.45	3.00	4.00
GC2WtFrLftBmUp	ezs	4.00	4.00	165.00	4.00	0.00	4.00	4.00
GC3RdyInSuprts	ezs	4.00	4.00	165.00	4.00	0.00	4.00	4.00
GC3RdyToFinlzP	ezs	7.00	7.00	156.43	6.64	0.98	4.00	7.00
GntryCrneRdyToL	ezs	12.00	13.00	60.00	4.73	4.07	0.00	12.00
LddCrnRdyToPsh	ezs	0.00	0.00		0.00	0.00	0.00	0.00
LddCrneRdyToMvD	ezs	1.00	1.00	90.00	0.55	0.50	0.00	1.00
LddTrckIdle	ezs	0.00	1.00	45.00	0.27	0.45	0.00	1.00
PrprdBmRdyToP	ezs	0.00	0.00		0.00	0.00	0.00	0.00
UnldCrnRdyToLBm	ezs	0.00	0.00		0.00	0.00	0.00	0.00

Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur	MinD	MaxD	AvInt	SDInt	MinI	MaxI
BmDlvryToGCrne	0	1	45.00	45.00	30.00		30.00	30.00				
BmLnchToSpn7	0	0										
BmPlcmntFrPrprt	0	0										
BmPlcmntOnSuprt	0	3	0.00	0.00	20.00	0.00	20.00	20.00	0.00	0.00	0.00	0.00
LddCrnStpSpn7	0	0										
LftngBmUpToCrn	0	0										
MvngUpUnldCrn	0	6	0.00	20.00	20.00	0.00	20.00	20.00	4.00	8.94	0.00	20.00
PrprdBmRdyToLd	0	0										
PrprtnOfBmOnGrn	0	0										
RtrnUnldCrnToAS	0	13	0.00	120.00	30.00	0.00	30.00	30.00	10.00	14.77	0.00	30.00
UnldCrnStpSpn7	0	6	20.00	40.00	10.00	0.00	10.00	10.00	4.00	8.94	0.00	20.00
UnlddCrnLock	0	13	30.00	150.00	15.00	0.00	15.00	15.00	10.00	14.77	0.00	30.00
UnlddTrckRdyToH	0	1	75.00	75.00	10.00		10.00	10.00				

The Future Events List is empty at simulation time 165.00

Figure 6.19 Simulation output report sheet for initial developed model on Span 7

As previously mentioned, it should be possible to interpret the output in a way that allows the study to compare the model concept with the concept of the real-world operation. In this step, the formulated assumptions should also be assessed.

6.7.3 COMPARISON ANALYSIS

To conduct a comparison, first, specific parts of the results should be selected which address the logic of resource utilisation, Activity completion, duration of the Activity and the interdependencies between model elements. As shown in the description of results in Section 6.2, the following results could illustrate the system behaviour and, consequently, help with this comparison analysis:

- current amount of content at the time of the report (Cur);
- total amount of resources to ever enter (Tot) the Queue;
- total number of items which have started (Tot) in Activities;
- time at which the first instance started (1stSt);
- time at which the last instance started (LstSt); and
- average duration (AvDur) of Activities.

Therefore, in the following sections, first, the Queues' results and then the aforementioned results for Activities are discussed.

Table 6.12 presents the outcome of discussions about the Cur and Tot results for the Queues. The simulation results of the current amount of content (Cur) and the total amount of content ever entered (Tot) into the Queues are then compared with the actual operation. This made it possible for the current research study to identify whether or not the logic of resource utilisation in the developed model conformed with the logic applied in the real-world operation. In cases where the logic applied in the developed model did not match that of the concept of the real-world operation, red font is used to present the interpretations.

Table 6.12 Assessing the model through interpretation of Cur results for Queues

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
BmRdyFrPreprtn	0.00	The computed Cur shows that this Queue does not have any content at the time of the report.	At time 40, this Queue should feed the required resource, which is the unprepared super T-beam, into Ac.3 (BmPlcmntFrPrprt). By completion of this task, the super T-beam is prepared and in the Ready state for the next step of the process. In other words, later on, the super T-beam is not in this state. Therefore, at the end of the project (SimTime), the resource will no longer be available in this state.	0.00	The computed Tot from the simulation shows that no content has ever entered this Queue, although having a prepared super T-beam in the Ready state is one of the required conditions for performing the Activity: LftngBmUpToCrn.
BmRdyToLftUp	0.00	The computed Cur shows that this Queue does not have any content at the time of the report.	At time 0, the super T-beam is on the truck that has stopped under the gantry crane. The availability of this super T-beam is one of the conditions for the commencement of BmDlvryToGCrne (Ac.1). When the required conditions for Ac.1 are all available, Ac.1 starts. Thirty (30) minutes later, the super T-beam is on the gantry crane. Thus, the state of the super T-beam changes when moved from the truck to the gantry crane.	1.00	As the computed Tot shows, the total number of resource units entered in this Queue is 1. According to the fieldwork project, at the start of the operation, the super T-beam should be in a Ready state on the truck. Otherwise, the first task cannot start.
BmRdyToPlc	1.00	The computed Cur shows that this Queue comprises 1 resource unit of the material at the time of the report. The type of the	At time 30, by completion of the first task (BmDlvryToGCrne [Ac.1]), the super T-beam has changed to the Ready state to be placed on the ground. In this situation, the super T-beam on the gantry crane should wait for the unloaded truck to leave.	1.00	In the real-world project, after delivering the super T-beam to the gantry crane, the unloaded truck can leave the gantry area. Therefore, this is the time to place the super T-beam on the ground and carry out the beam

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
		material held in this Queue is the super T-beam, now in the Ready state to be placed on the ground.	Therefore, at time 40, this resource can enter the new step of the process: Ac.4 (BmPlcmntFrPrprt). By entering the resource (the super T-beam) into this Activity, no more of this resource in this state is available.		preparation to start the launching process. The total number of resource units in this state entered in this Queue should be 1. Therefore, in undertaking the comparison, the computed Tot from the model matches that of the real-world project.
GC12RdyRtrnCrn	0.00	The computed Cur shows that this Queue does not have any content at the time of the report.	At time 185, when Ac.12 is about to start, one of the required conditions is the resource formed by the combination of three (3) persons from Crew 1 (GC1) and four (4) persons from Crew 2 (GC2). The combined crews need to be in the Ready state to enable Ac.12 to start. The resource does not hold this state after Ac.12 is completed. In other words, by the completion of the operation at its life-cycle time, no more resource content in this state is available. In a comparing the simulation result and the real-world project, the model is seen to work properly in accordance with the concept of the real-world project.	13.00	In the real-world project, after completion of Ac.11, Crews 1 and 2 (GC1 and GC2) should combine as a new group to work on the return of the unloaded gantry crane to auxiliary support. The total number of personnel of this new crew is 3+4=7. The combined crew plays this role only once in the system. Therefore, by the completion of Ac.13, there is no crew in this state in the system. Comparing the computed Tot from the simulation to the real-world project shows that, in relation to this Queue, the simulation has not modelled the real-world concept.
GC1Idle	4.00	The content of the resource assigned to the GC1 Queue, in accordance with Table 6., is 3 units. By the completion of the	At time 30, when Ac.1 is performed, the state of Crew 1 (GC1), which was Ready to deliver the super T-beam from the truck to the gantry, is changed to Idle. The crew stay in this state until they have to enter the super T-beam preparation process at	4.00	By the completion of Ac.1, Crew 1 (GC1) switches their state to Idle. The number of resource units holding the Idle state is 3 due to the assignment of Ac.1 to Crew 1 (GC1). However, the computed Tot shows

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
		operation, the content should not exceed 3 resource units.	time 40. However, at SimTime, no content of this resource is in this state. However, as is shown by the computed Cur from the simulation, the model has not been developed properly, and it should be revised.		that the total amount of the resource units holding this state in the system is 4. Thus, the developed model requires further revision in this regard.
GC1RTLftUpUnldC	0.00	The computed Cur shows that this Queue does not have any content at the time of the report.	At time 135, Crew 1 (GC1), in the Ready state, provides the condition for starting Ac.9. In this state, the crew moves the gantry crane to the support where the super T-beam is to be placed. By completion of Ac.9 at time 155, this crew should immediately change its state and be ready to lift up the unloaded crane. By switching to this state and holding another Ready state, the crew provides the condition for commencing the next Activity. Therefore, the crew is no longer in this state. At SimTime, the Cur should be 0 resource units. Comparing the computed Cur and the logic of the fieldwork project shows the proper modelling of this Queue.	6.00	In order to start Ac.9, Crew 1 (GC1) should be in the Ready state to move the loaded gantry crane to the support. Later, after it has performed Ac.9, the crew should be in the Ready state to remote the unloaded crane to the top of the span and prepare it for its return. Therefore, the total number of resource units holding this state is 3. Comparison of the real-world project to the computed Tot shows that the developed model needs revision in this regard.
GC1RdyLftUnldCr	3.00	The computed Cur shows that this Queue holds 3 resource units at the time of the report. However, according to the concept of the real-world project, this	Crew 1 (GC1) at time 40 holds the Ready state to move the loaded gantry crane down onto the ground. At time 50, when Ac.3 is completed, Crew 1 (GC1) switches its state to the Ready state for lifting up the unloaded crane as the crew has to change some settings on the winches and cable to make the crane ready for the next process.	3.00	After the completion of Ac.3, Crew 1 (GC1), which has been in the Ready state for moving the loaded gantry crane to the ground, now switches their state to another role. When Ac.3 is completed, Crew 1 (GC1) should be in the Ready state to load the super T-beam onto the crane, and then to

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
		cannot happen.	The crew stays in this Ready state until Ac.5 starts (at time 65). The crew's state changes immediately after the completion of Ac.5. Therefore, towards the end of the operation, the resource in this state will no longer be available.		lift the crane up. This crew plays the explained role once only. Therefore, the computed Tot should be 3 resource units.
GC1RdyToMvCrD	0.00	The computed Cur shows that this Queue does not have any content at the time of the report.	At time 135, when the process of super T-beam placement on the support is in progress, Crew 1 (GC1) should be in the Ready state to move the loaded gantry crane down. The crew holds this state until the completion of Ac.9. Then, at time 155 and later on, Crew 1 (GC1) holds this Ready state. This means that towards the end of the operation, at SimTime, the computed Cur related to this Queue should be 0 resource units.	3.00	By completion of Ac.8, the loaded gantry crane stops over the span. Crew 1 (GC1) should then be in the Ready state to remote the loaded crane downward. It is obvious that the total amount of resource units in this state is equal to the number of resources assigned to Crew 1 (GC1). In comparing the real-world project to the computed Tot, the developed model is in alignment with the state of the crew.
GC1RdyToMvLdCrD	0.00	The computed Cur shows that this Queue does not have any content at the time of the report.	At time 40, Crew 1 (GC1), which was in an Idle state after the completion of Ac.1, should switch to the Ready state. This crew should be in the Ready state to conduct the loaded gantry crane to the ground allowing the delivered super T-beam to be placed on the ground. This crew stays in this state from time 40 for no longer than 10 minutes in duration. Therefore, comparing this concept to the computed Cur shows that the developed model is in line with this	0.00	After delivering the super T-beam from the truck, the loaded gantry crane should be remoted downward to place the beam on the ground. At this time, Crew 1 (GC1), in the Ready state, is in charge of performing this task. Therefore, the total number of resource units to enter this Queue should be 3.

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
			Queue.		
GC1RdyToPckBm	2.00	The computed Cur shows that this Queue contains 2 resource units at the time of the report.	At this early step, with the super T-beam on the loaded truck waiting to be picked up, Crew 1 (GC1), in the Ready state, participates by providing the required condition for starting the delivery of the super T-beam onto the gantry crane. The crew should be in the Ready state to remote the crane to pick up the beam from the truck and should continue in the Ready state until the time and situation are at the point when the truck can leave the gantry area. Therefore, this crew stays in the Ready state for no longer than 30 minutes (the required duration for the completion of Ac.1). In comparison of the simulation result (the computed Cur) and the concept of the real-world project, the developed model is in line with this Queue.	3.00	One of the required conditions to start the first task in the system is the availability of Crew 1 (GC1) in the Ready state to pick up the super T-beam from the truck. The total number of resource units that is able to hold the Ready state in the system is 3.
GC1RdyToPshCrn	3.00	The computed Cur shows that this Queue contains 3 resource units at the time of the report.	With the completion of Ac.6 at time 95, Crew 1 (GC1) should be ready to push the loaded gantry crane forward. Their Ready state provides one of the conditions for commencing Ac.7. This crew holds the Ready state for 30 minutes until Ac.7 is completed. Later, at time 125, the Queue with Crew 1 (GC1) in this state is not available in the system. However, the computed Cur from the simulation shows that at SimTime, this Queue still contains	3.00	After the completion of Ac.6, it is time to start launching the loaded gantry crane toward the span. Therefore, Crew 1 (GC1) should be in the Ready state to launch the loaded crane forward. As also shown by the computed Tot from the simulation, the total number of resource units involved in this state in the system is 3.

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
			3 resource units. Thus, the developed model needs revision in this regard.		
GC1WtfrGC23	3.00	The computed Cur shows that this Queue contains 3 resource units at the time of the report. Comparing the model with the concept of the real-world project shows that this Queue holds 3 resource units in this state as the model stopped exactly at time 215, after which the model did not consider any further Activity.	At time 185, as explained before, Crews 1 and 2 (GC1 and GC2) combined to work on returning the gantry crane to auxiliary support. For about 30 minutes, these two crews should work as one combined resource until Ac.12 was completed. Then, Crew 2 (GC2) should continue their work of locking the crane at auxiliary support, and Crew 1 (GC1) should wait for them to get their job done. This waiting state does not mean the Idle state, as Crew 1 (GC1) may be called for remoting to support Crew 2 (GC2) with the locking process. On the other hand, the locking process should take 15 minutes; therefore, Crew 1 (GC1) holds this state for 15 minutes from time 185 to time 215.	16.00	When Ac.12 is completed, Crew 1 (GC1) should wait for the rest of the crews to complete their tasks. As the number of resource units assigned to the Crew 1 Queue is 3, the computed Tot should also be 3 resource units, whereas the number of resource units in the computed Tot is 16.Therefore, the model should be revised in relation to this Queue.
GC23RdyToPlcBm	5.00	The computed Cur shows that this Queue contains 5 resource units at the time of the report.	At time 135, Crews 2 and 3 (GC2 and GC3) combine to work as one resource to place the super T-beam on its support. These 8 people contribute to the completion of Ac.9 for about 20 minutes. After that, they separate into their two crews in different states. Crew 2 (GC2) should be ready to return the gantry crane, and Crew 3 (GC3) should work on the support to finalise the placement of the super T-beam. Therefore, at time 155 later	8.00	When the loaded gantry crane stops over the span where the super T-beam is to be placed, Crews 2 and 3 (GC2 and GC3) combine as one crew to start placing the beam on its support. The total number of resource units able to hold this state is 4+4=8. Comparing the computed Tot from the simulation to the developed model around this Queue shows that the developed model conforms to the

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
			on, no resource has that state in the system. As shown by comparing the computed Cur from the simulation to the real-world concept, the developed model's concept should be revised.		concept of the real-world project.
GC2RdyToPrpartn	5.00	The computed Cur shows that this Queue contains 5 resource units at the time of the report, all of which are in the Ready state for preparation of the Super T-beam. In contrast, the concept of the real-world project shows that at the time of the report, this crew does not hold this state. Towards the end of the operation, Crew 2 (GC2) is in the Ready state for returning the gantry crane and locking it on the auxiliary support. However, the developed model should be revised in this regard.	Crew 2 (GC2) starts their work at time 0 in the Waiting state. They have to wait until time 30, when the gantry crane places the Super T-beam on the ground. This crew then changes to the Ready state for preparation of the beam. In this way, the crew can meet one of the conditions for the commencement of Ac.3. This crew stays in the same state until Ac.3 and Ac.4 are completed. Then, at time 65, Crew 2 (GC2) switches to another Waiting state to allow Ac.5 to start.	5.00	After the completion of Ac.1, Crew 2 (GC2) changes from the Waiting state while the gantry crane places the super T-beam on the ground to the Ready state for preparation of the beam. This crew now should be in the Ready state to proceed to Ac.3. The total number of resource units assigned to this Queue is 4; therefore, the computed Tot should be 4, not 5 resource units.

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
GC2RdyToPshBm	4.00	The computed Cur shows that this Queue contains 4 resource units at the time of the report, with these units in the Ready state to move the loaded gantry crane forward. On the other hand, according to the concept of the real-world project, toward the end of operation, Crew 2 (GC2) is in the Busy state for locking the unloaded crane at the auxiliary support. Therefore, the developed model should be revised in this regard.	At time 65, Crew 2 (GC2) is involved in the completion of Ac.5 with the crew in the Busy state for about 15 minutes. Then at time 80, Crew 2 (GC2) should be in the Ready state for moving the loaded gantry crane forward. The crew will stay in this state for 55 minutes until Ac.8 is completed. Then they should join Crew 3 (GC3) to prepare support for the placement of the super T-beam. Therefore, this crew holds the Ready state from time 80 to time 135.	4.00	When the prepared super T-beam is loaded to the gantry crane, Crew 2 (GC2) should be in the Ready state to launch the loaded crane forward to the span. The availability of Crew 2 (GC2) in this state is one of the required conditions for starting Ac.7. Therefore, the computed Tot from the simulation shows that the total number of resource units entering this state is 4.
GC2RdyToRtrnCrn	1.00	The computed Cur shows that this Queue contains 1 resource unit at the time of the report.	Crew 2 (GC2) at time 155 should be in the Ready state to return the unloaded gantry crane to the auxiliary support. Therefore, the crew can provide Ac.10 with one of its required conditions. This crew, by holding this state, is involved in the completion of Ac.10 and Ac.11 for about 30 minutes but for no longer than time 185. As seen when comparing the computed Cur from the	7.00	After completion of Ac.9, Crew 2 (GC2), which was involved in the combined crew, switches to another state. Crew 2 (GC2) is now working as a separate group from Crew 3 (GC3) and is in the Ready state for moving the unloaded gantry crane up. However, the total number of resource units able to enter into this

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
			simulation, the logic of the developed model does not conform to that of the real-world project. Therefore, the model should be revised in this regard.		state in the system is 4.
GC2WtFrCrnPBm	3.00	The computed Cur shows that this Queue contains 3 resource units at the time of the report.	As previously explained, at time 0, Crew 2 (GC2) should be in the Waiting state for the gantry crane for about 30 minutes to allow the crane to pick up the super T-beam from the truck. When the crane loads the beam, this crew should be in the Ready state for preparation of the beam, placed on the ground at time 30. Crew 2 (GC2) is involved in this role until Ac.3 is completed. Therefore, toward the end of operation, this resource no longer has this role.	4.00	At the start of the operation, Crew 2 (GC2) should be in the Waiting state for delivering the super T-beam from the truck to the gantry crane. This crew holds this state only once in the system. Therefore, the total number of resource units which enters this Queue is equal to the number of resource units that have been assigned to Crew 2 (GC2)'s resource category.
GC2WtFrLftBmUp	4.00	The computed Cur shows that this Queue contains 4 resource units at the time of the report.	When Ac.4 is completed at time 65, Crew 2 (GC2) should be in the Waiting state for Crew 1 (GC1) to start Ac.5. When Crew 1 (GC1) moves the loaded gantry crane up, Crew 2 (GC2) should immediately switch to the Ready state to push the loaded crane toward Span 7. This means that resources from Crew 2 (GC2) in the Waiting state are only available in the system from time 65 to time 80, and no longer. However, the computed Cur from the simulation shows that Crew 2 (GC2) at the end of operations is still in the Waiting state. Therefore, the	4.00	When Ac.4 is completed, Crew 2 (GC2) should be in the Waiting state for Crew 1 (GC1) to remote the loaded crane upward. As shown by the computed Tot from the simulation, the total number of resource units that play this role in the system is 4.

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
			model should be revised in this regard.		
GC3RdyInSuprts	4.00	The computed Cur shows that this Queue contains 4 resource units at the time of the report.	Crew 3 (GC3) at time 95 should be in the Ready state in support to carry out the required preparation. This crew is involved in this role until Ac.8 finishes at time 125, after which Crew 3 (GC3) no longer needs to play this role in the system. As can be seen in comparing the computed Cur from the simulation, the developed model does not conform to the logic of the real-world project.	4.00	One of the required conditions for starting Ac.7 is the availability of Crew 3 (GC3) in the Ready state at the support, where the super T-beam is going to be placed. Therefore, the total number of resource units that could enter into this state is equal to 4, which is the total number of resource units assigned to this Queue.
GC3RdyToFinlzP	7.00	The computed Cur shows that this Queue contains 7 resource units at the time of the report, while the maximum amount of resource units assigned to this Queue is 4.	At time 135, Crew 3 (GC3) is involved in the new role. This crew should work on the finalisation of the placement of the super T-beam at its support. This Busy state is the last state that Crew 3 (GC3) holds in the system. Usually this crew is in the Busy state in this role for about 80 minutes (almost to the end of the operation). As can be seen in comparing the computed Cur from the simulation, the developed model's logic does not match that of the real-world project. Therefore, the model should be revised with regard to this Queue.	7.00	At the completion of Ac.9, Crew 3 (GC3) switches to the Ready state for finalising the placement of the super T-beam on its support. However, Crew 3 (GC3) works as a separate group from Crew 2 (GC2) in this state, and it should contain 4 resource units.
GntryCrneRdyToL	12.00	The computed Cur shows that this Queue contains 7 resource units at the time of the report, while the	The gantry crane at time 0 should be in the Ready state to pick up the super T-beam from the loaded truck. The crane holds this state until Ac.1 is completed. At time 30, the crane's state changes from unloaded to	13.00	Early in the operation, when the loaded truck is in the gantry area, the gantry crane should be in the Ready state to pick up the super T-beam from the truck. The number of

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
		maximum amount of resources assigned to this Queue is 1. Therefore, it is impossible for this Queue to hold 12 resource units.	loaded, with the crane in this role only for 30 minutes and no longer, early in the operation. As is obvious in comparison with the computed Cur from the simulation, the concept of the developed model in relation to this Queue has not been properly modelled.		resource units assigned to this Queue is 1. Therefore, it is impossible to accept the computed Tot as 13.
LddCrnRdyToPsh	0.00	The computed Cur shows that this Queue does not contain any resource units of the gantry crane type that hold the Ready state at the time of the report.	At time 95 when Ac.6 is completed, the gantry crane should be in the Ready state for moving forward as it carries the super T-beam. The crane stays in this role until the completion of Ac.9 with the beam placed on its support. Then, from time 155 to the end of the operation, the crane is unloaded and is in the Ready state for moving backward to the auxiliary support to be locked at time 215.	0.00	At the completion of Ac.6, the prepared super T-beam is loaded onto the gantry crane. The loaded crane should then be in the Ready state for launching toward Span 7: otherwise, Ac.7 cannot start, and the operation would stop at this step. As shown by comparing the computed Tot from the simulation, the developed n=model should be revised in relation to this Queue.
LddCrneRdyToMvD	1.00	The computed Cur shows that this Queue contains 1 resource unit of the gantry crane type that holds the Ready state for moving down at the time of the report. In comparing this to the logic of the real-world project, the gantry crane could hold this state from	As explained about GntryCrneRdyToL, at time 30 when Ac.1 is completed, the gantry crane's state switches to new state. It has now loaded the super T-beam and should be in the Ready state for placing the beam on the ground. The loaded crane should then be in the Waiting state for 10 minutes, until the truck leaves the gantry area. Therefore, by the completion of Ac.3, the crane no longer stays in this state.	1.00	By the completion of Ac.1, the loaded gantry crane is in the Ready state to be remoted downward to place the beam on the ground. Therefore, the total number of resource units which enter into this state in the system is 1.

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
		time 30 to time 40. However, the developed model needs to be revised in this regard.			
LddTrckIdle	0.00	The computed Cur shows that this Queue does not contain any resource units of the loaded truck type that hold the Idle state at the time of the report.	At time 0, the loaded truck should be available in the gantry area. The availability of this resource is one of the required conditions for the commencement of Ac.1. Unless the loaded truck is not parked in alignment with the axles of the gantry crane, it does not need to move. It then stays in the Idle state until Ac.1 is completed at time 30. As shown by the computed Cur from the simulation, the Queue holding the loaded crane in the Idle state is not available at the end of the operation.	1.00	The computed Tot shows that 1 resource unit in total has been entered into this Queue. As shown in the model, 1 resource unit should enter the system at time 0. Otherwise, the system cannot start performing “BmDlvryToGCrne”. The same situation can be seen in the real-world project.
PrprdBmRdyToP	0.00	The computed Cur shows that this Queue does not contain any resource units of the beam type that hold the Ready state at the time of the report.	At time 65, after preparation of the delivered super T-beam for launching, the beam takes on its new role. It should be in the Ready state to be lifted by the gantry crane and launched to Span 7. For about 15 minutes, until Ac.5 is completed, this resource stays in the same role. After time 80, the beam is no longer in this state.	0.00	One of the required conditions for lifting up the super T-beam from the ground is the availability of the prepared beam on the ground. Otherwise, the operation cannot proceed to the next step.
UnldCrnRdyToLBm	0.00	The computed Cur shows that this Queue does not contain any	At time 65, when the preparation of the super T-beam on the ground finishes, the unloaded gantry crane should be ready to	0.00	One of the required conditions for commencing Ac.5 is that the unloaded crane should be in the

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Does the model conform to the concept of the real-world project according to Tot?
		resource unit of the gantry crane type that is unloaded and in the Ready state for lifting the super T-beam.	pick up the beam. The crane stays in this role until Ac.6 is completed. Its state then changes to the Loaded state as it should be ready to launch the beam toward Span 7.		Ready state to move down and pick up the super T-beam from the ground. Therefore, the total number of resource units that enter this Queue is 1.

At this point, the model's concept has undergone assessment against the logic of the real-world project through interpreting the Queues' results. The Activities' results are also important in this context; for example, the results shown as 1stSt present the sequence of the performance of Activities. Comparing the 1stSt to the sequence of tasks in the fieldwork project can give the modeller good insight into understanding the extent to which the developed model behaves in accordance with the real-world project. Moreover, as seen in the following sections, the developed model was assessed according to Tot, 1stSt, AvDur and LstSt.

Based on the EZStrobe handbook (descriptions of the output of Activities are presented see Section 6.2, Table 6.4), the computed Tot results for Activities present the total number of items which started. On the other hand, the assumptions of the model can help to assume the amount of Tot. For example, for completion of the operation modelled here, it is assumed that each Activity should be completed once only; therefore, each Activity includes only one instance, with the model also developed for one round of operation.

Table 6.13 presents the interpretation and assessment of the computed Tot results against the concept of the real-world project. The following tables (Tables 6.14–6.16) analyse the sequence of the completion of Activities which is compared to the real-world fieldwork. Moreover, the interpretation of the AvDur outcomes enables the study to assess the links between Activities and Queues, as well as to the life cycle of the operation. The incorrectness of the developed model is illustrated by the quick review of the AvDur results as, for many of the Activities in this initial simulated model, AvDur has not been computed.

Table 6.13 Assessing the model through interpretation of Tot results for Activities

Interpretation of results of computed Tot at SimTime for Activities			
Activity	**Tot**	**Does the model conform to the concept of the real-world project according to Tot?**	**Accepting or rejecting?**
BmDlvryToGCrne	1	The computed Tot shows that this Activity has been started once. Therefore, according to the real-world project, the modelling of this Activity seems to be accurate.	√
BmLnchToSpn7	0	According to the real-world project, this Activity should be performed to allow the next Activity (LddCrnStpSpn7) to start later. The computed Tot of 0 shows that the model should be revised around	X

Interpretation of results of computed Tot at SimTime for Activities			
Activity	**Tot**	**Does the model conform to the concept of the real-world project according to Tot?**	**Accepting or rejecting?**
		this Activity.	
BmPlcmntFrPrprt	0	Similar to the BmLnchToSpn7 Activity, the model should be revised around BmPlcmntFrPrprt for which the computed Tot result is 1.	X
BmPlcmntOnSuprt	3	The computed Tot for this Activity illustrates that the Activity has been started 3 times, whereas the model has been developed with 1 round of operation and based on the assumption of 1 instance of this Activity. Therefore, the model should be revised in this regard.	X
LddCrnStpSpn7	0	The logic of the real-world project indicates that this Activity should be performed once, so the computed Tot should be 1. The Tot result of 0 in this case illustrates inaccuracy of the model around this Activity.	X
LftngBmUpToCrn	0	The logic of the real-world project indicates that this Activity should be performed once, so the computed Tot should be 1. The Tot result of 0 in this case illustrates inaccuracy of the model around this Activity.	X
MvngUpUnldCrn	6	The computed Tot for this Activity indicates that it has been started 6 times, whereas the model has been developed with 1 round of operation, and based on the assumption of 1 instance of this Activity. Therefore, the model should be revised in this regard.	X
PrprdBmRdyToLd	0	The computed Tot for this Activity indicates that the Activity has not yet started whereas, according to the logic of the real-world project, this Activity should be started within SimTime.	X
PrprtnOfBmOnGrn	0	The computed Tot for this Activity indicates that the Activity has not yet started whereas, according to the logic of the real-world project, this Activity should be started within SimTime.	X
RtrnUnldCrnToAS	13	The computed Tot for this Activity indicates that this Activity has been started 13 times, whereas the model has been developed with 1 round of operation, and the assumption of 1 instance of this Activity. Therefore, the model should be revised in this regard.	X
UnldCrnStpSpn7	6	The computed Tot for this Activity indicates that this Activity has been started 6 times, whereas the	X

Interpretation of results of computed Tot at SimTime for Activities			
Activity	**Tot**	**Does the model conform to the concept of the real-world project according to Tot?**	**Accepting or rejecting?**
		model has been developed with one round of operation, and the assumption of 1 instance of this Activity. Therefore, the model should be revised in this regard. However, the criteria have not been met in this case.	
UnlddCrnLock	13	The computed Tot for this Activity indicates that this Activity has been started 13 times, whereas the model has been developed with one round of operation, and the assumption of 1 instance of this Activity. Therefore, the model should be revised in this regard.	X
UnlddTrckRdyToH	1	The computed Tot shows that this Activity has been started once by the time of the report (SimTime). This shows that the modelling of this Activity has been done accurately.	X

Table 6.14 Assessing the model through interpretation of 1stSt results for Activities

Interpretation of results of computed 1stSt at SimTime for Activities				
	Activity	1stSt	Interpretations	Accepting or rejecting?
Ac.1	BmDlvryToGCrne	45.00	In cases for which 1stSt has not been computed, the model should be revised. In cases for which 1stSt has been computed, the sequence can be described as follows: 1- Ac.4 and Ac.7 started at the early stage 2- 20 minutes later, Ac.11 has been started 3- The process continued by starting Ac.12 at time 30, Ac.1 at time 45 and Ac.13 at time 75. Referring to the description of Activities in Table 6.10, and the initial conceptual model presented and discussed in Section 6.5, it is apparent that the computed sequences do not match the concept of the real-world project. Therefore, the model should be revised with regard to the sequence of Activities.	X
Ac.2	BmLnchToSpn7			
Ac.3	BmPlcmntFrPrprt			
Ac.4	BmPlcmntOnSuprt	0.00		
Ac.5	LddCrnStpSpn7			
Ac.6	LftngBmUpToCrn			
Ac.7	MvngUpUnldCrn	0.00		
Ac.8	PrprdBmRdyToLd			
Ac.9	PrprtnOfBmOnGrn			
Ac.10	RtrnUnldCrnToAS	0.00		
Ac.11	UnldCrnStpSpn7	20.00		
Ac.12	UnlddCrnLock	30.00		

Interpretation of results of computed 1stSt at SimTime for Activities				
	Activity	1stSt	Interpretations	Accepting or rejecting?
Ac.13	UnlddTrckRdyToH	75.00		

Table 6.15 Assessing the model through interpretation of 1stSt and LstSt results for Activities

Interpretation of results of computed 1stSt and LstSt at SimTime for Activities				
Activity	1stSt	LstSt	Interpretations	Accepting or rejecting?
BmDlvryToGCrne	45.00	45.00	Comparing the sequence of the Activity to the real-world project, the results show that the logic associated with this Activity is accurate.	√
BmLnchToSpn7			As no amounts have been computed for 1stSt and LstSt, this means that this Activity has not been started. Referring to the computed Tot, the same issue could be noticed; therefore, the model should be revised in this regard.	X
BmPlcmntFrPrprt			As no amounts have been computed for 1stSt and LstSt, this means that this Activity has not been started. Referring to the computed Tot, the same issue could be noticed; therefore, the model should be revised in this regard.	X
BmPlcmntOnSuprt	0.00	0.00	The computed amount for 1stSt is equal to that for LstSt. The results also show that this Activity starts and finishes at the same time as in the real-world project.	√
LddCrnStpSpn7			As no amounts have been computed for 1stSt and LstSt, this means that this Activity has not been started. Referring to the computed Tot, the same issue could be noticed; therefore, the model should be revised in this regard.	X
LftngBmUpToCrn			As no amounts for 1stSt and LstSt have been computed, this means that this Activity has not been	X

Interpretation of results of computed 1stSt and LstSt at SimTime for Activities				
Activity	1stSt	LstSt	Interpretations	Accepting or rejecting?
			started. Referring to the computed Tot, the same issue could be noticed; therefore, the model should be revised in this regard.	
MvngUpUnldCrn	0.00	20.00	The computed amount for 1stSt is not equal to that for LstSt. When the model includes Activities each of which has only 1 instance, then the time at which the first instance could be started should be the same as the time at which the last instance could be started. Therefore, the model needs to be revised around this Activity.	√
PrprdBmRdyToLd			As no amounts for 1stSt and LstSt have been computed, this means that this Activity has not been started. Referring to the computed Tot, the same issue could be noticed; therefore, the model should be revised in this regard.	X
PrprtnOfBmOnGrn			As no amounts for 1stSt and LstSt have been computed, this means that this Activity has not been started. Referring to the computed Tot, the same issue could be noticed; therefore, the model should be revised in this regard.	X
RtrnUnldCrnToAS	0.00	120.00	The computed amount for 1stSt is not equal to that for LstSt. When the model includes Activities each of which has only 1 instance, then the time at which the first instance could be started should be the same as the time at which the last instance could be started. Therefore, the model needs to be revised around this Activity.	X
UnldCrnStpSpn7	20.00	40.00	The computed amount for 1stSt is not equal to that for LstSt. When the model includes Activities, each of which has only 1 instance, then the time at which the first instance could be started should be the same as the time at which the last	X

Interpretation of results of computed 1stSt and LstSt at SimTime for Activities				
Activity	1stSt	LstSt	Interpretations	Accepting or rejecting?
			instance could be started. Therefore, the model needs to be revised around this Activity.	
UnlddCrnLock	30.00	150.00	The computed amount for 1stSt is not equal to that for LstSt. When the model includes Activities, each of which has only 1 instance, then the time at which the first instance could be started should be the same as the time at which the last instance could be started. Therefore, the model needs to be revised around this Activity.	X
UnlddTrckRdyToH	75.00	75.00	The computed amount for 1stSt is equal to that for LstSt. Therefore, the criterion is met in this case. The results also show that this Activity starts and finishes at the same time as in the real-world project.	√

Table 6.16 Assessing the model through interpretation of AvDur results for Activities

Interpretation of results of computed AvDur at SimTime for Activities			
Activity	AvDur		Interpretations
BmDlvryToGCrne	30.00	Sum=135 minutes	The comparison of the AvDur simulation results with the duration taken for task completion in the real-world fieldwork, as presented in Table 7.3, shows that the developed model includes some Activities which have never been carried out.
BmLnchToSpn7			
BmPlcmntFrPrprt			
BmPlcmntOnSuprt	20.00		
LddCrnStpSpn7			
LftngBmUpToCrn			
MvngUpUnldCrn	20.00		
PrprdBmRdyToLd			
PrprtnOfBmOnGrn			
RtrnUnldCrnToAS	30.00		
UnldCrnStpSpn7	10.00		
UnlddCrnLock	15.00		
UnlddTrckRdyToH	10.00		

From the previous discussions and analysis, it would seem that the developed model does not conform to the logic of the real-world operation. The reasons could be attributed to the inaccuracy of the logic applied in the model through the links between Activities and Queues.

As explained in Section 6.2, the message prompted by running STROBOSCOPE should also be considered to see whether or not the model includes an unlimited cycle. The prompted message for the current developed model is presented in Figure 6.20, showing there is no issue regarding an unlimited cycle in the developed model. However, the model needed to be revised in accordance with the discrepancies identified and presented in Tables 6.13–6.16.

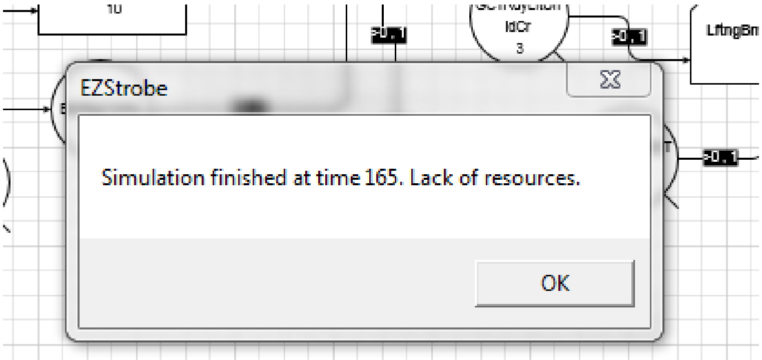


Figure 6.20 Simulation message

6.7.4 REVISION PHASE

In the first revision, the early part of the operation has been modelled, starting from the super T-beam delivery by truck to the gantry crane and finishing by lifting up the beam. The study then tried to expand the model step by step toward the placement of the beam and returning the gantry crane to the auxiliary support. The details of the models are presented and discussed in the next subsections.

6.7.4.1 Model I

To resolve the issues encountered in the initial developed model, as described in Section 6.4.2, the study at this stage tried to minimise the number of states of the resources, and also the number of Activities included in the model. All the effort was focused on simplifying the early part of the operation with the aim being to support the study by assessing the model's accuracy. In this model, Model I, the super T-beam was not considered to be a resource. The model included two types of resources instead of three.

The crews were assigned to two states, Ready and Idle, with their annotations simplified (see Table 6.17 and Table 6.18) in comparison with the annotations in the previous model. In Model I, the annotations of the Queues included the states of the resources. In Tables 6.17 and 6.18, details of the model are summarised. As with the initial model development, assumptions were then formulated, and the model was re-run.

Table 6.17 Information on Activities in Model I

Sequence of Activities	Activity	Duration (minutes)
Ac.1	BeamRdyToPick	15
Ac.2	BeamLftUp	5
Ac.3	LiftingBeamUp	5
Ac.4	UnlddTrckLeavs	5
		30

Table 6.18 Information on resources/Queues in Model I

<table>
<tr><th>Types of Resource</th><th>Resources</th><th>ACD model annotation according to Queue's state</th><th>Maximum Content</th></tr>
<tr><td rowspan="6">Human Resources (Gantry Crew)</td><td rowspan="2">Gantry Crew 1</td><td>Crew1Idle</td><td rowspan="2">3</td></tr>
<tr><td>Crew1Ready</td></tr>
<tr><td rowspan="2">Gantry Crew 2</td><td>Crew2Idle</td><td rowspan="2">2</td></tr>
<tr><td>Crew2Ready</td></tr>
<tr><td rowspan="2">Gantry Crew 3</td><td>Crew3Idle</td><td rowspan="2">2</td></tr>
<tr><td>Crew3Ready</td></tr>
<tr><td rowspan="2">Machine</td><td>Crane</td><td>GntcrnRdy</td><td>1</td></tr>
<tr><td>Truck</td><td>LddTrckIdle</td><td>1</td></tr>
</table>

To revise the model at this phase, the following assumptions are made:

1- Each Activity includes one instance.

2- The model is only for one round of operation.

3- The maximum content of resources is in accordance with the information presented in Table 6.19.

4- The total duration for the completion of one round of operation is as shown in Table 6.19.

5- The model is based on durations collected for the first beam placement operation and assigned to the model with the non-probability function

6- The sequence of the performance of Activities according to the real-world project is presented in Table 6.20. At time 0, as shown in the sequence, Ac.1 is started. The time required for the completion of Ac.1 is 15 minutes. At time 15, when the super T-beam is ready to be lifted by the gantry crane, both Ac.2 and Ac.3 can be started simultaneously. The required time for the completion of these two Activities is 5 minutes. Now hanging from the gantry crane, the beam needs to be moved down to the ground. Therefore, in Model I, the previous Activity was modelled as a Combi (Conditional Activity). The reason is that the lifted up beam should wait for 5 minutes before entering the next step of the operation (moving the beam down and preparation of the beam on the ground, with these Activities not included in this part of the model).

7- In this model, the amount of resources used for the completion of Activities would be considered to be released through the released link, with the release modelled by arrow links and relevant annotations as shown on Figure 6.21.

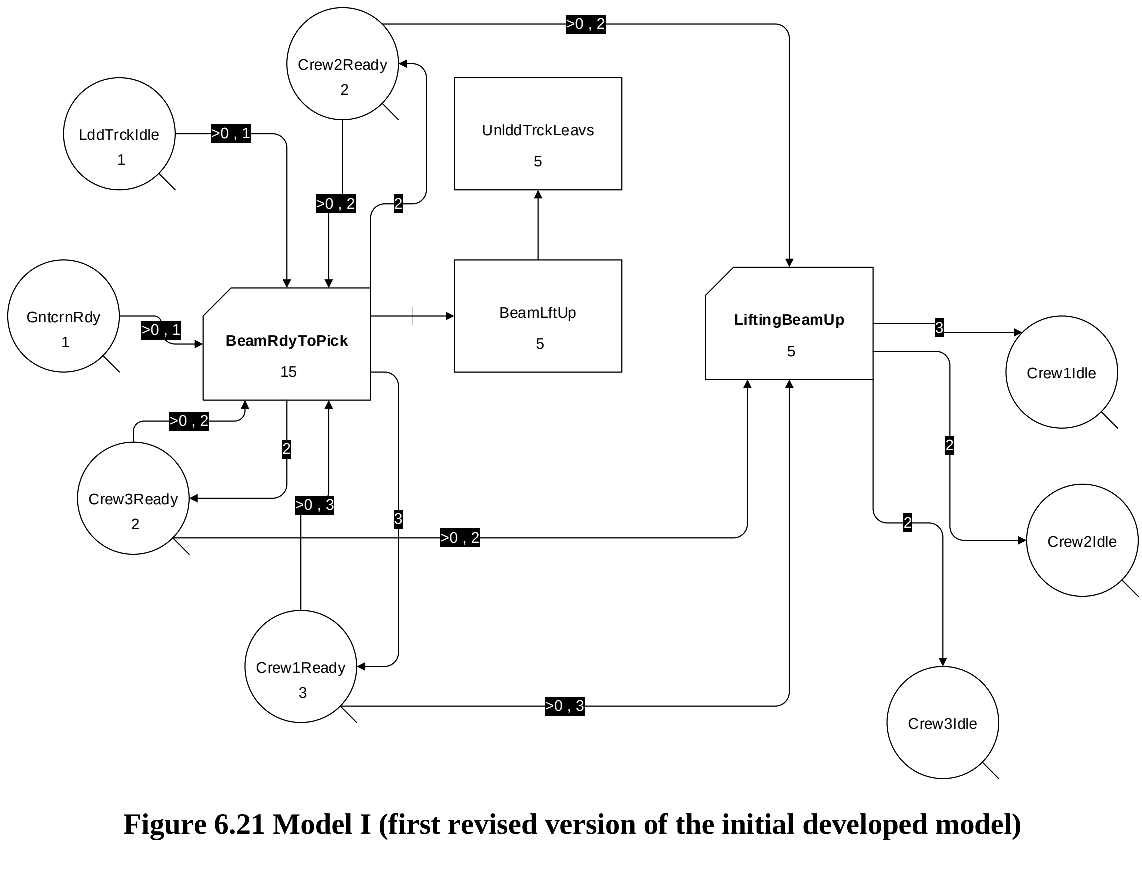


Figure 6.21 Model I (first revised version of the initial developed model)

The model was then developed as presented in Figure 6.21. It was then simulated by running EZStrobe which led to achieving the outputs presented in Tables 6.19 and 6.20.

Table 6.19 Simulation output on Model I: Results for Queues

Ac.	Queue	Res	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
1	Crew1Idle	ezs	3.00	3.00	5.00	0.60	1.20	0.00	3.00
2	Crew1Ready	ezs	0.00	6.00	0.00	0.00	0.00	0.00	3.00
3	Crew2Idle	ezs	2.00	2.00	5.00	0.40	0.80	0.00	2.00
4	Crew2Ready	ezs	0.00	4.00	0.00	0.00	0.00	0.00	2.00
5	Crew3Idle	ezs	2.00	2.00	5.00	0.40	0.80	0.00	2.00
6	Crew3Ready	ezs	0.00	4.00	0.00	0.00	0.00	0.00	2.00
7	GntcrnRdy	ezs	0.00	1.00	0.00	0.00	0.00	0.00	1.00
8	LddTrckIdle	ezs	0.00	1.00	0.00	0.00	0.00	0.00	1.00

Table 6.20 Simulation output on Model I: Results for Activities

Ac.	Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur*	MinDur	MaxDur	AvInt*	SDInt*	MinInt*	MaxInt*
1	BeamLftUp	0	1	15.00	15.00	5.00		5.00	5.00				
2	BeamRdyToPick	0	1	0.00	0.00	15.00		15.00	15.00				
3	LiftingBeamUp	0	1	15.00	15.00	5.00		5.00	5.00				
4	UnlddTrckLeavs	0	1	20.00	20.00	5.00		5.00	5.00				

**Outputs for these parameters have not been computed in this model*

As explained in Section 6.7, after simulating a model, verification and validation are required to help a modeller to identify how the developed model matches the logic of the real-world operation. Therefore, in Table 6.21, the Cur and Tot results for Queues are analysed. Verification and validation of the model are then continued by interpreting the simulation output for Activities. In cases where conformance between the model's concept and the real-world fieldwork has failed, the interpretations are presented in red font (see Table 6.22).

All of the steps for verification and validation including assessment of the output of Queues and Activities are presented in Tables 6.21 and 6.22.

Table 6.21 Assessing Model I through interpretation of Cur results for Queues

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Maximum amount of resources assigned	Does the model conform to the concept of the real-world project according to Tot?
Crew1Idle	3.00	The computed Cur shows that this Queue contains 3 resource units at the time of the report.	At the end of the operation, when the prepared super T-beam is lifted to the gantry crane, Crew 1 (GC1) should wait for the rest of the project. As the rest of the real-world project has not been included in this developed model, it is considered that Crew 1 (GC1) stays in the Idle state. As can be seen by comparing the Cur result from the simulation, the logic of the developed model matches the real-world project.	3.00	3	At the end of the operation, when Ac.4 is completed, the crews involved in the beam delivery process change their states to the Idle state. Therefore, the total number of resource units entered in this state should be equal to the number of resource units assigned to the associated Queues.
Crew1Ready	0.00	The computed Cur shows that this Queue does not contain any resource units at the time of the report.	At time 0, Crew 1(GC1) is ready to deliver the super T-beam from the truck to the gantry crane. This crew holds the state for about 15 minutes until	6.00	3	Early at the start of the operation, one of the required conditions for the commencement of Ac.1 is the availability of Crew 1 (GC1) in the Ready state. This crew

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Maximum amount of resources assigned	Does the model conform to the concept of the real-world project according to Tot?
			Ac.1 is completed. However, this crew does not stay in this state in the system any longer. This means that by the end of the operation (as modelled and described in Section 6.7.4.1), none of the Crew1 resource units in the Ready state is available.			later participates in the completion of Ac.4. The total number of resource units entered into this state are: 3+3=6 as 3 resource units enter this Queue at time 0 when the operation starts, and 3 resource units are released back to this Queue at time 15 when Ac.1 is completed.
Crew2Idle	2.00	Similar to Crew1Idle	Similar to Crew1Idle	2.00	2	Similar to Crew1Idle
Crew2Ready	0.00	Similar to Crew1Ready	Similar to Crew1Ready	4.00	2	Crew 2 (GC2) is in the same situation as has been explained for Crew 1 (GC1). As the number of resource units assigned to this Queue is 2 units, then multiplying the 2 units by two as they enter and re-enter this Queue results in 4 units as the total number of resource units that enter

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Maximum amount of resources assigned	Does the model conform to the concept of the real-world project according to Tot?
						this Queue.
Crew3Idle	2.00	Similar to Crew1Idle	Similar to Crew1Idle	2.00	2	Similar to Crew1Idle
Crew3Ready	0.00	Similar to Crew1Ready	Similar to Crew1Ready	4.00	2	Crew 3 (GC3) is in the same situation as has been explained for Crew 2 (GC2). As the number of resources assigned to this Queue is 2 units, then multiplying the 2 units by two as they enter and re-enter this Queue results in 4 units as the total number of resource units that enter this Queue.
GntcrnRdy	0.00	The computed Cur shows that this Queue does not contain any resource units of the gantry crane type in the Ready state at the time of the report.	At time 0, the gantry crane should be ready to pick up the Super T-beam from the truck. This state will last until Ac.15 is completed. As can be seen by comparison with the Cur result from the simulation, the logic of the developed model	1.00	1	At time 0, one of the required conditions for the commencement of Ac.1 is the availability of the gantry crane in the Ready state. This Queue feeds only one Activity. Therefore, the total number of resource units that enter

Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Tot	Maximum amount of resources assigned	Does the model conform to the concept of the real-world project according to Tot?
			conforms to the concept of the real-world project.			this Queue is 1.
LddTrckIdle	0.00	The computed Cur shows that this Queue does not contain any resource units of the loaded truck type in the Idle state at the time of the report.	At time 0, the loaded truck should be available to meet one of the required conditions for the commencement of Ac.1. After Ac.1 is completed, the loaded truck then switches to another state to become the unloaded truck.	1.00	1	As has been explained about GntcrnRdy, the total number of resource units that enter this Queue is 1.

Table 6.22 Assessing Model I through interpretation of results for Activities

Interpretation of results of computed Tot at SimTime for Activities			
Activity	Tot	Interpretations	Accepting or rejecting?
BeamLftUp	1	The developed model includes Activities that comprise only one instance. The model is developed for only one round of operation. Therefore, the computed Tot should be 1. As the results show, the current model matches the concept of the real-world project from the perspective of performing the Activities.	√
BeamRdyToPick	1		
LiftingBeamUp	1		
UnlddTrckLeavs	1		
Interpretation of results of computed 1st and Lst at SimTime for Activities			
Activity	1stSt	Interpretation	Accepting or rejecting?
BeamLftUp	15.00	The results show that the computed 1stSt is equal to the computed LstSt, thus, meeting the model assumptions. However, the sequence of Activities in the next table shows that the performance of Activities does not follow the logic of the real-world project. Therefore, the model should be revised in this regard.	X
BeamRdyToPick	0.00		
LiftingBeamUp	15.00		
UnlddTrckLeavs	20.00		
Interpretation of results of computed 1st at SimTime for Activities			
Activity	Sequence according to 1stSt	Interpretation	Accepting or rejecting?
BeamLftUp	2	According to the description of the operation, the Activity, LiftingBeamUp, should be the last Activity that could be started at time 20. Moreover, the	X
BeamRdyToPick	1		
LiftingBeamUp	2		
UnlddTrckLeavs	3		

Interpretation of results of computed Tot at SimTime for Activities			
Activity	Tot	Interpretations	Accepting or rejecting?
		Activities, UnlddTrckLeavs and BeamLftUp, should be started simultaneously. Therefore, the model does not conform to the logic of the real-world project.	
Interpretation of results of computed AvDur at SimTime for Activities			
Activity	AvDur	Real Duration	Comparison of the computed AvDur results to the real-world duration shows that the developed model works properly from the perspective of the real-world project life cycle.
BeamLftUp	5.00	5.00	
BeamRdyToPick	15.00	15.00	
LiftingBeamUp	5.00	5.00	
UnlddTrckLeavs	5.00	5.00	

Assessment of Model I showed that the revision had made improvements to the initial developed model in Figure 6.17. However, the interpretations in red font in some of the above tables indicate the need to further revise the model (see Figure 6.21). Therefore, the study went through several revisions of the model to identify the causes and how these issues should be revised.

Following up on the fieldwork study, collecting more data on the placement of subsequent beams for Ramp 1/Span 7, fitting the distribution and parameterising the model could also be experimented with in subsequent revised models. Other issues encountered by the modeller (the researcher in this study) in the development of these revised versions of the model are listed below, with the aim being to resolve them within the next phase of the simulation procedure:

1- Uncomputed SDDur, AvInt, SDInt, MinInt and MaxInt due to the development of the model as a closed loop (a cycle) or as a model which included Activities comprised of one instance, 2- Uncomputed 1stSt, and

3- Error: time limit reached.

Taking into consideration the above issues and undertaking continued revision of the model led the study to achieve a model for which the simulation results could finally conform to the logic of the real-world project. The associated details are discussed in the next chapter where the current study presents the main phase of data collection and analysis.

6.8 SUMMARY

The main purpose of the preliminary study presented in this chapter was to identify how the data collected from the document analysis could support the current research in achieving its objectives (see Section 1.2.2). The development of the models presented in this chapter illustrated the steps required in simulating an operation. The chapter also indicated where to add these steps in the procedures identified in previous studies. Furthermore, the presentation of the development of these models and the associated simulation experiments has shown the need to record more details of the work process to enable the modeller (the researcher) to achieve a proper model.

Moreover, by conducting a preliminary study, initial model development and the revision phase, the current research was able to draft the framework for the implementation of EZStrobe (see Figure 6.22).

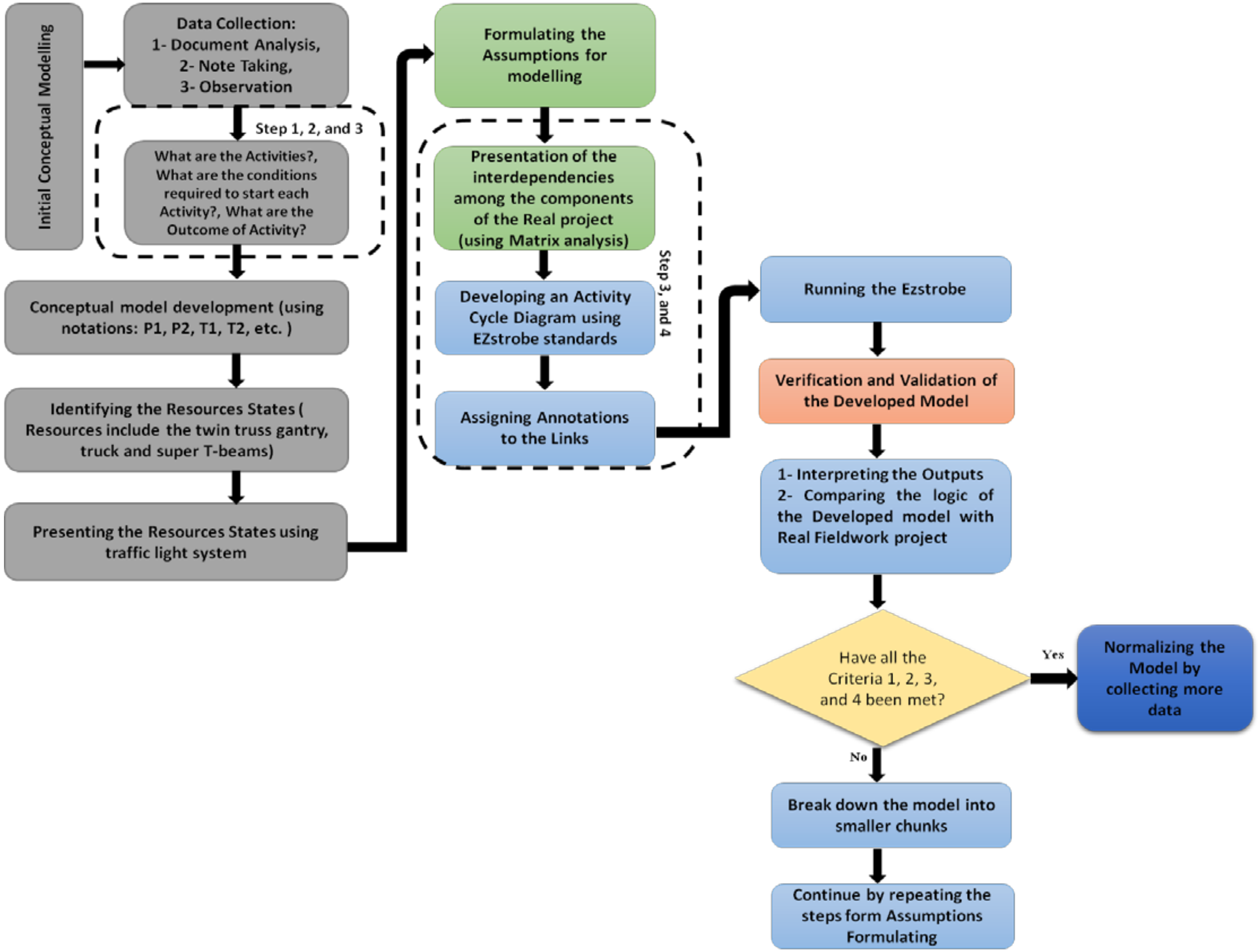


Figure 6.22 Preliminary framework for implementation of EZStrobe in simulating a construction operation

Figure 6.22 summarises the steps completed in the development of models in Chapter 6. In addition, this framework presents the simulation steps proposed by previous studies, indicating the other steps needed to achieve a proper simulation model. This initial framework was then utilised in the main phase of the current study (see Chapter 7). As the main phase of the study collected more data as the Great North Road Interchange (GNRI) operations progressed, the researcher had the opportunity to implement this framework in a model with a larger data set and, consequently, was able to apply revisions, if required (see Section 7.2).

CHAPTER 7

DATA COLLECTION AND ANALYSIS:

(II) THE MAIN PHASE OF THE STUDY

7.0 INTRODUCTION

This chapter presents the data collection and analysis processes which were completed within the main phase of the study, in which the construction of Ramps 1 and 4 (see Figure 6.2) was undertaken.

Section 7.1 presents the revision of the final model developed in the preliminary study. The major focus of continuing the study from the revision phase was to resolve the issues raised in the development of the final model in Chapter 6. Furthermore, Section 7.1 presents the details of the data collected from the construction of Ramp 1 (comprising 40 data sets) and the data analysis undertaken for the revision of the developed model.

In Section 7.2, the description of the simulation process continues by developing a framework for the implementation of EZStrobe and, in Section 7.3, by examining some of EZStrobe's capabilities, such as the "Probabilistic Branch" function, parameterising the model, and animation and scenario analyses.

In Section 7.4, the developed framework is used in the simulation of the GNRI gantry launching operation for which 54 more data sets were available. These data were collected from the construction of Ramp 4 and were added to the modelling process to normalise the simulated model. Section 7.4 also presents the relevant discussions.

7.1 FINAL REVISION OF DEVELOPED MODEL

In order to complete this step, the first task was to sort out the collected data from the construction of Ramp 1 to clearly present the behaviour of the system, with this including the content of resources, sequence of Activities, and interactions between Activities and resources. Then, in line with the main objective of the study, the capabilities of EZStrobe were explored through probability distribution function (PDF) analysis of the "Sampling Function Builder" function (see Section 6.6.4).

In Section 7.1.1, the collected data are presented. Discussion then continues on the analysis of the data using EasyFit software and on the process of simulating the operation.

7.1.1 DATA COLLECTION FOR FINAL REVISION

The current research continued the fieldwork study by collecting data using participant observation and from field notes taken during the construction of Ramp 1. The database, as previously developed and presented in Chapter 5, was used to record information at this step. Furthermore, the researcher attended Last Planner System (LPS) meetings held by the case study organisation to collect more information on the project's progress, as well as details on the look-ahead plan and master schedule. In this way, the research could maintain the chain of evidence and enhance the reliability of the data. Two of the most significant contributions of the data collection using the developed database were recording the most common constraints (called "Reasons for non-completion" in the LPS), and adding more details to the master plan according to the behaviour of the system in the real-world project. These details, including the types of beam and limitations on the number of resources leading to the project's progress failing to meet its milestones, thus became highlighted throughout this phase of the study. Moreover, the study was prompted to use this information to explore scenario analysis, one of the capabilities of EZStrobe, and to find out how the relevant simulated model could help with understanding the system behaviour and with more accurately enhancing the level of planning.

Information collected on the Activities, duration of the completion of Activities, resources and the content of resources is presented in Tables 7.1–7.3. The modelling procedure, as practised in the previous chapter, then continued with the formulation of assumptions.

Table 7.1 Information on resources and their contents

Human Resources	
Crew 1	includes 3 persons who mainly remote the gantry crane
Crew 2	includes 2 persons who operate the winches and cable settings
Crew 3	includes 2 persons who carry out preparation, stressing, etc.
Crew 4	includes 2 persons who work on the support for placing the beam on the span

Table 7.2 Information on Activities and their sequences

Activity	Model annotation	Sequence according to the fieldwork operation
Beam Ready To Move	BeamRdyToPick	Ac.1
Unloaded Truck Leaves	UnlddTrckLeavs	Ac.2
Placing the Beam on the Ground	PlcBmToGround	Ac.3
Finishing the Placement of Beam on the Ground)	FnshPlcGrnd	Ac.4
Preparation of the Beam to be Loaded into the Gantry	Preparation	Ac.5
Finishing the Preparation	FinishPrpartn	Ac.6
Lifting up the Prepared Beam by the Gantry	LftngUpPrprdBm	Ac.7
Beam is Hanging **from the Gantry**	FinishHangngBm	Ac.8
Gantry is loaded and ready to be Launched	BmRdyLnch	Ac.9
Gantry Crane starts Launching	GntCrnStartLnch	Ac.10
Beam is ready to be Moved Down to its place on the Span	BmMvDwn	Ac.11
Finishing the Placement	FnshPlcmnt	Ac.12
Unloaded Gantry should be Moved Up	GntryMveUp	Ac.13
Unloaded Gantry should be Ready to Get Back to Auxiliary Supports	GntryRdyBck	Ac.14
Gantry starts to be Moved Back to Auxiliary Supports	GntryPushBck	Ac.15
Gantry is Locked to Auxiliary Supports	FinishLocking	Ac.16
	End	Ac.17

Table 7.3 Activity duration in studied case project (minutes)

	BeamRdyToPick	UnlddTrckLeaves	PlcbmToGround	FnshPlcGround	Preparation	LftngUpprprdBm	FinishHangngBm	BmRdyLnch	GntCrnStartLnch	BmMvDwn	FnshPlcmnt	GntryMveUp	GntryRdyBck	GntryPushBck	FinishLocking
1	33	12	7	5	35	12	5	15	5	20	35	10	12	10	5
2	35	10	7	5	35	10	8	12	5	25	30	10	15	10	5
3	35	8	6	5	25	10	5	15	8	25	35	15	10	5	10
4	25	8	5	3	30	10	5	10	10	20	30	10	10	5	5
5	20	10	8	5	30	8	10	10	5	20	30	10	8	15	5
6	20	10	10	5	25	10	10	10	5	20	25	10	8	15	5
7	20	10	10	5	20	10	8	15	8	25	20	10	10	10	5
8	25	8	10	4	30	10	10	10	8	25	20	8	10	15	8
9	20	8	12	6	35	10	8	8	8	20	25	8	10	15	12
10	22	10	8	5	25	12	8	10	15	25	30	8	10	18	12
11	25	12	8	5	25	10	8	10	8	25	35	8	12	15	8
12	20	10	6	6	25	8	12	10	8	20	30	12	10	20	5
13	20	10	8	6	30	8	15	10	15	20	35	10	8	15	5
14	20	8	10	3	25	8	12	8	10	15	45	10	10	15	5
15	35	10	12	5	25	10	10	12	12	20	25	15	8	10	10
16	30	8	8	5	20	10	10	10	10	25	25	8	15	15	5
17	33	10	6	5	18	15	12	12	10	20	35	10	10	10	5

	BeamRdyToPick	UnlddTrckLeaves	PlcbmToGround	FnshPlcGround	Preparation	LftngUpprprdBm	FinishHangngBm	BmRdyLnch	GntCrnStartLnch	BmMvDwn	FnshPlcmnt	GntryMveUp	GntryRdyBck	GntryPushBck	FinishLocking
18	30	10	8	6	25	10	8	15	10	20	30	10	15	15	5
19	35	10	8	6	25	10	8	10	8	25	30	15	10	20	8
20	25	10	10	4	35	10	8	10	15	20	25	8	10	20	10
21	25	12	10	5	30	10	12	10	12	25	25	12	10	22	5
22	20	15	12	5	30	8	10	8	10	20	30	8	8	20	12
23	25	12	10	5	30	10	10	12	10	15	35	10	10	20	5
24	38	10	10	4	30	10	8	10	12	20	40	10	10	15	5
25	35	10	8	5	30	10	8	5	15	15	35	10	12	20	5
26	33	10	8	6	35	12	10	10	15	20	35	8	12	10	10
27	30	10	6	5	25	10	10	10	8	20	35	5	12	20	8
28	33	8	10	5	25	10	8	10	10	20	25	5	8	18	8
29	25	10	6	5	20	12	10	12	10	20	40	5	12	20	5
30	25	10	6	6	25	10	8	15	10	20	30	10	15	20	5
31	25	10	6	5	25	10	12	8	15	20	30	8	12	25	5
32	20	10	6	5	30	15	10	12	10	15	35	10	10	18	5
33	25	12	10	5	30	10	10	10	10	20	35	12	10	20	10
34	25	15	10	5	30	10	8	8	10	20	40	8	10	20	10
35	25	12	8	6	30	12	8	10	10	25	30	10	8	20	5

	BeamRdyToPick	UnlddTrckLeaves	PlcbmToGround	FnshPlcGround	Preparation	LftngUpprprdBm	FinishHangngBm	BmRdyLnch	GntCrnStartLnch	BmMvDwn	FnshPlcmnt	GntryMveUp	GntryRdyBck	GntryPushBck	FinishLocking
36	30	12	8	5	35	12	10	10	8	10	30	10	8	15	10
37	30	10	10	5	35	10	12	15	10	15	25	10	8	15	5
38	35	15	12	5	30	10	10	10	10	10	35	10	8	10	8
39	25	8	10	5	35	12	10	12	10	20	35	8	10	20	5
40	20	10	6	6	30	10	8	10	10	20	30	8	12	20	10
Ave. Dur.	26.925	10.325	8.475	5.05	28.325	10.35	9.3	10.725	9.95	20.125	31.25	9.55	10.4	16.025	6.975
Min. Dur.	20	8	5	3	18	8	5	5	5	10	20	5	8	5	5
Max. Dur.	38	15	12	6	35	15	15	15	15	25	45	15	15	25	12
Total average duration (average cycle time)=213.75 minutes															
Total maximum duration (maximum cycle time)=303 minutes															

7.1.2 FORMULATING THE ASSUMPTIONS

1. Each Activity includes one instance. The time at which the first instance starts is the same as the time that the last instance starts. This means that simulation should compute 1stSt equal to LstSt.
2. The model is only for one round of the operation (i.e. placement of intermediate beam).
3. The maximum content of resources is in accordance with the information presented in Table 7.1.
4. The interactions between resources and Activities as well as the flow direction of resources should match the matrix developed based on the real-world project (Figure 7.1).
5. The duration of the cycle time varies between total average duration and total maximum duration of work elements as shown in Table 7.3 (also see Table 7.9 where fit distribution is analysed and discussed). As the study at this step collected data for more than one beam, fitting distribution could be applied to the duration of Activities within this model.
6. The sequence of the performance of Activities according to the real-world project is in accordance with what is presented in Table 7.2.

The final version, as shown in Figure 7.2, includes four groups of crew, 17 Activities (Normal and Combi elements) and 17 Queues. Information on the developed model is included in Tables 7.4–7.6.

As previously explained, to find out how to resolve the issues encountered in the preliminary phase, the modelling was conducted first in three small parts; then all parts were combined to build up the final model. The Activities and Queues included in each part are presented in Table 7.4 and Table 7.5.

Table 7.4 Information on Activities and Queues in developed model

Part	Activity information		Queue information
	Activity (Combi and Normal node)	Sequence of Activities	Queue utilisation in each part
Part 1	BeamRdyToPick	Ac.1	LddTrckIdle
	UnlddTrckLeavs	Ac.2	GntcrnRdy
	PlcBmToGround	Ac.3	Crew1Ready
	FnshPlcGrnd	Ac.4	Crew2Ready
	Preparation	Ac.5	Crew3Ready
	FinishPrpartn	Ac.6	BmRdyFrPlc
			BmRdyFrPrprtn
Part 2	LftngUpPrprdBm	Ac.7	BmRdyToBHung
	FinishHangngBm	Ac.8	Crew1RdyLnch
	BmRdyLnch	Ac.9	Crew2Rdy
			Crew3Rdy
Part 3	GntCrnStartLnch	Ac.10	BmRdyOnTpofSpn
	BmMvDwn	Ac.11	Crew1
	FnshPlcmnt	Ac.12	Crew2
	GntryMveUp	Ac.13	Crew3
	GntryRdyBck	Ac.14	Crew4Rdy
	GntryPushBck	Ac.15	GntryRdyLock
	FinishLocking	Ac.16	
	End	Ac.17	

Table 7.5 Information on resources in developed model

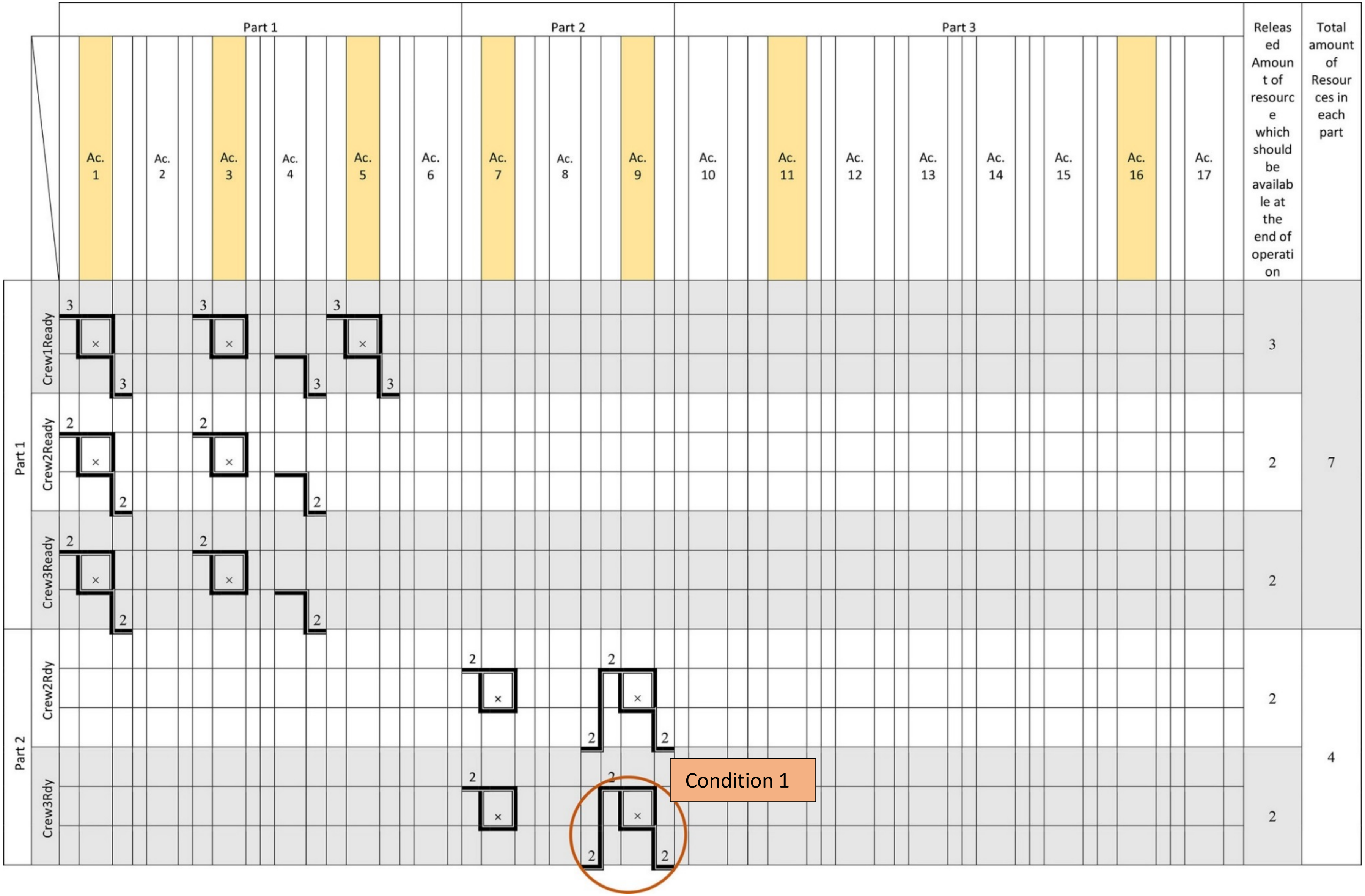
Types of Resource	Resources	ACD model annotation	Assigned content	Model part number
Human Resources (Gantry Crew)	Crew 1	Crew1Ready	3	1
		Crew1RdyLnch	3	2
		Crew1	3	3
	Crew 2	Crew2Ready	2	1
		Crew2Rdy	2	2
		Crew2	2	3
	Crew 3	Crew3Ready	2	1
		Crew3Rdy	2	2
		Crew3	2	3
	Crew 4	Crew4Rdy	2	3
Material	Super T-beam	BmRdyFrPlc	1	1
		BmRdyFrPrprtn	1	1
		BmRdyOnTpofSpn	1	3
		BmRdyToBHung	1	1
Machine	Crane	GntcrnRdy	1	1
		GntryRdyLock	1	3
	Truck	LddTrckIdle	1	1

In addition, the interactions between Combis, Normal Activities and Resources which were applied in this revised version are analysed and presented in Table 7.6 and Figure 7.1.

Table 7.6 illustrates how Queues and Activities interact with each other in each part of the model. In Figure 7.1, the matrix analysis of the transaction of resources between Queues and Combis has been designed in more detail. In this figure, it can be seen that the resources and their content flow through the feeding or releasing link drawn between Queue and Activity. Moreover, the amount of resources released by completion of the Activity is presented in this matrix. The thickness of the line is designed to present the flow of each resource between Queue and Activity, and vice versa. The Activities included in Table 7.6 are all the Combi type while, in Figure 7.1, both Combi and Normal elements are embedded to give insight into the developed model. The Combis have been highlighted in yellow shading. The flow of the resources shows how the required condition for the commencement of Combi elements has been met in this model.

Table 7.6 Interactions between Activities and Queues in different parts of system

		Part 1	Part 1	Part 1	Part 2	Part 2	Part 3	Part 3
	Combi / Queue	BeamRdyToPick (Ac.1)	PlcBmToGround (Ac.3)	Preparation (Ac.5)	LftngUpPrprdBm (Ac.7)	BmRdyLnch (Ac.9)	BmMvDwn (Ac.11)	FinishLocking (Ac.16)
Part 1	Crew1Ready	×	×	×				
Part 1	Crew2Ready	×	×					
Part 1	Crew3Ready	×	×					
Part 2	Crew1RdyLnch					×		
Part 2	Crew2Rdy				×	×		
Part 2	Crew3Rdy				×	×		
Part 3	Crew2						×	
Part 3	Crew1						×	
Part 3	Crew3						×	
Part 3	Crew4Rdy						×	×


Part 1
Part 2
Part 3
Ac. 1
Ac. 2
Ac. 3
Ac. 4
Ac. 5
Ac. 6
Ac. 7
Ac. 8
Ac. 9
Ac. 10
Ac. 11
Ac. 12
Ac. 13
Ac. 14
Ac. 15
Ac. 16
Ac. 17
Released Amount of resource which should be available at the end of operation
Total amount of Resources in each part
Crew1Ready
Crew2Ready
Crew3Ready
Crew2Rdy
Crew3Rdy
3
2
2
2
2
7
4
Condition 1

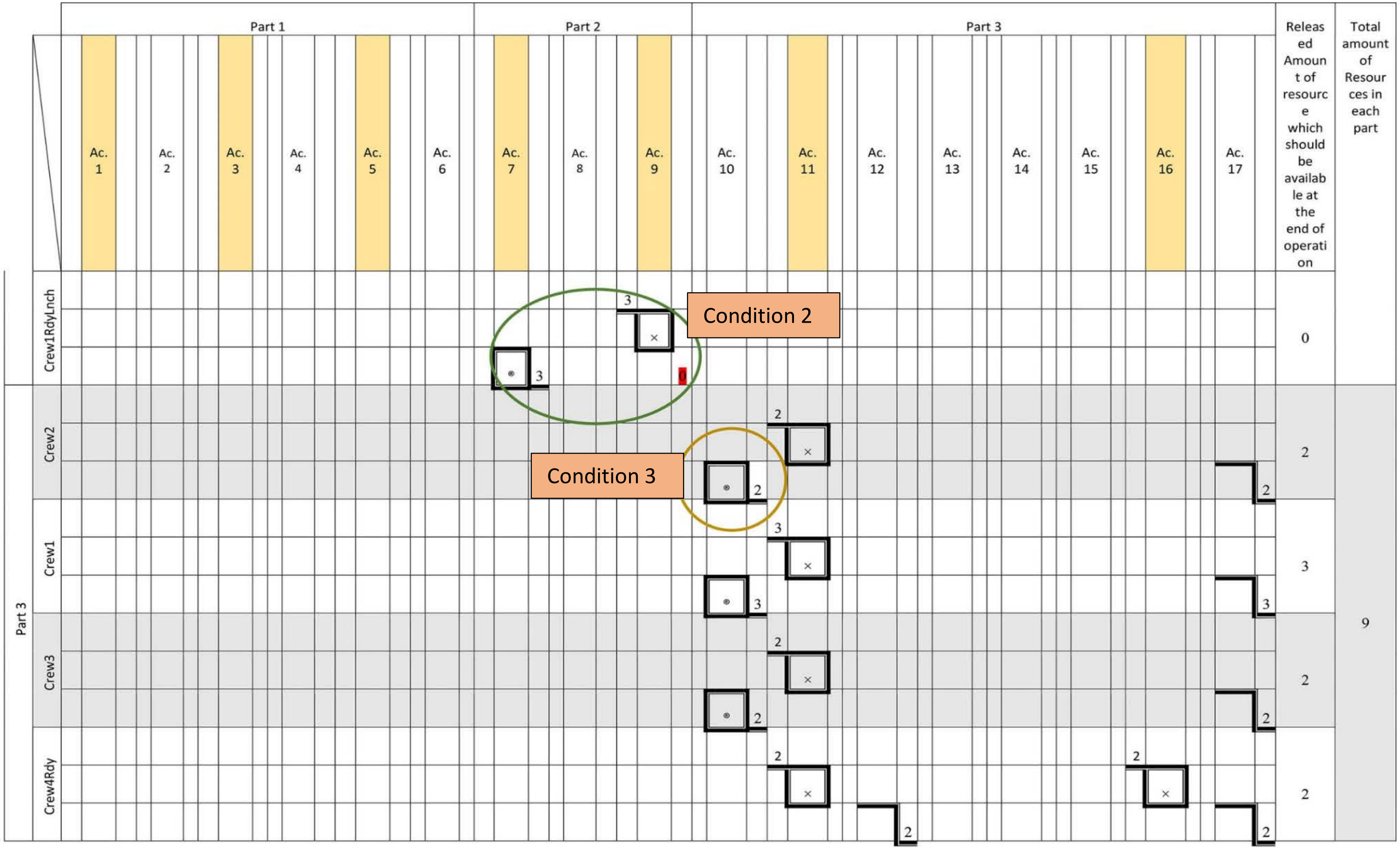


Figure 7.1 Matrix analysis of interdependencies of operation elements: Resource flow analysis

The following three different conditions are signposted in Figure 7.1 to help with the description of the interactions between resources:

1. Condition 1: With the completion of Ac.8, 2 resource units (Crew3Rdy) are released. These resource units is ready to be fed into the Combi shown as Ac.9. With the completion of Ac.9, these resource units are then released.
2. Condition 2 shows the specific situation when model development moves from Part 1 to Part 2. In order to complete the Combi shown as Ac.7, some resources from two different human resource types of Queue (Crew2Rdy and Crew3Rdy) are fed into the Combi. At this time, Crew 1 (comprising 3 persons) changes its work area from Part 1 to Part 2 of the model, with the crew becoming involved in the launching process when Ac.7 is completed. While Ac.7 is undertaken by two other crews, Crew1 carries out little jobs which are not included in this model. This is the reason why Crew1Ready Queue, which received its number of resource units after completion of the last Combi (Ac.5) in Part 1, has been presented with the different annotation "Crew1RdyLnch" in Part 2. As this crew's involvement is not direct involvement, it has also been removed from the model. Therefore, as the matrix analysis shows, this Queue receives the released number of resource units (the 3 persons assigned to Crew 1) after completion of Ac.7, and the crew goes directly to the Combi shown as Ac.9 to provide this Combi with the required conditions to start. The first cell with a dot shows that the completion of Ac.7 leads to the allocation of 3 persons in the Crew1RdyLnch Queue. The next cell with an 'x' sign shows the flow of Crew 1 into Ac.9. Once again, the Crew1RdyLnch is changing their job conditions from Part 2 to Part 3 then, with the completion of Ac.9, none of the resource units are going back to that Queue. It is assumed that Crew1RdyLnch is indirectly involved in the completion of Ac.10. Moreover, Crew 1, which is the released number of resource units from that Queue, is going to be allocated to the new Queue.
3. Condition 3 shows a cell embedded with a dot which means that, by the completion of the Activity corresponding to that cell (Ac.10), a specific number of resource units (in this case, Crew 2) is going back to its correspondent Queue.

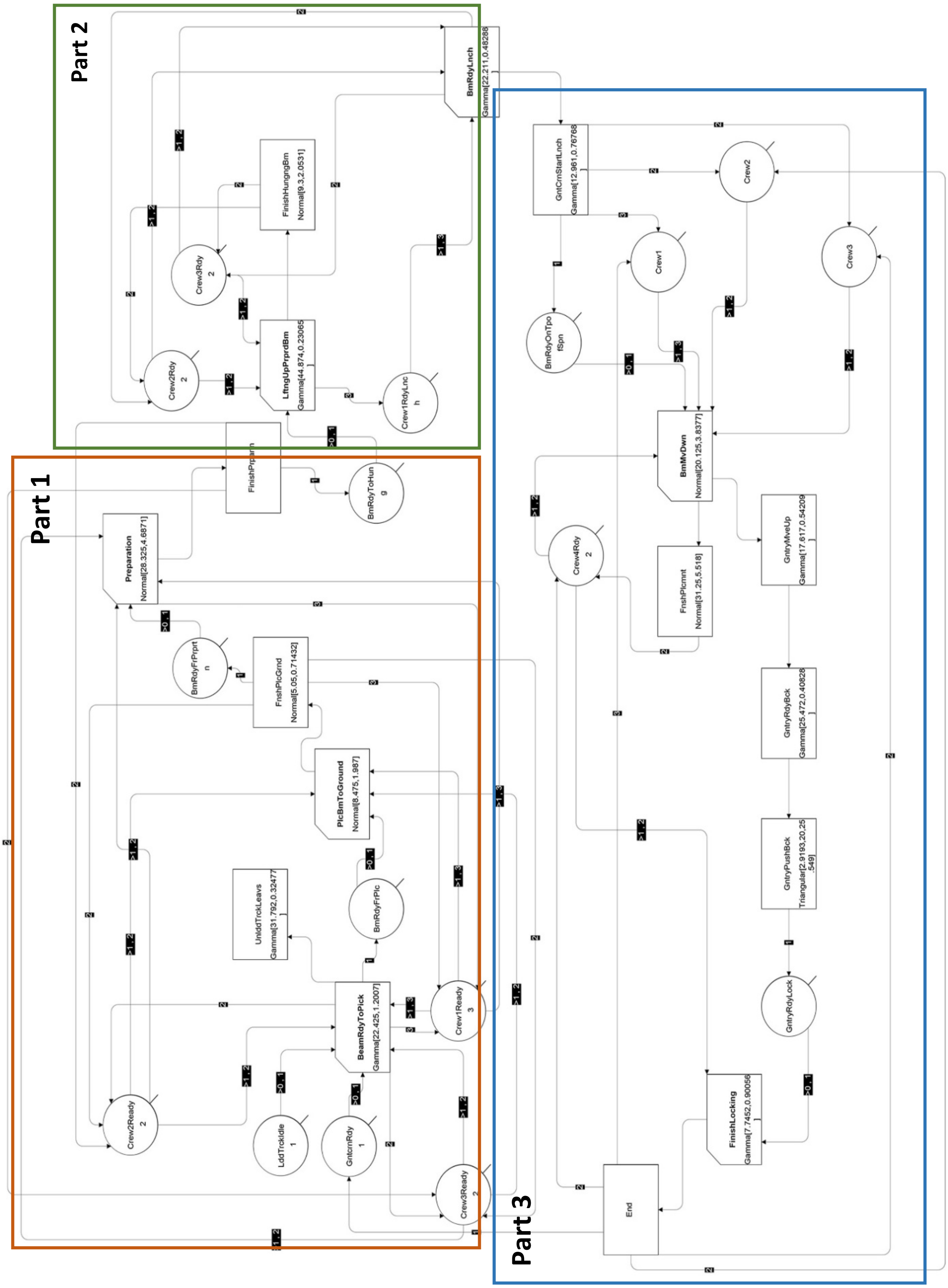


Figure 7.2 GNRI Strobe Model I (final version of simulated model developed for studied operation)

All elements of the real-world system's concept and its assumptions are addressed in these descriptions. The next section presents the process of assigning the best fit distribution to Combi and Normal Activities. As explained in Section 6.3, the PDF analysis is part of the simulation's Step 5 (see "Introduction to EasyFit" in Appendix 1).

7.1.3 ESTIMATING DURATION OF ACTIVITY: FITTING THE PROBABILITY DISTRIBUTION FUNCTION (PDF)

In this step, the study aimed to examine "Sampling Function", one of the capabilities of EZStrobe. This required the best fit distribution function to be identified for the duration of each Activity. As presented in Section 5.6, the study selected EasyFit software to fulfil the fit distribution analysis in this step. All of the data collected from the completion of operations for Ramp 1's construction were used in this phase (see Table 7.3). The duration of the completion of each Activity is presented in minutes. Furthermore, the average, minimum and maximum time required for the completion of Activities have been calculated and are presented in the final rows of Table 7.3.

The data were fed into EasyFit. According to the descriptions presented in Appendix 1, the distribution function which best fits each Activity's duration was then calculated. Prior to entering the selected distribution function into the EZStrobe model, EasyFit's output needed to be translated into the language/symbols used in EZStrobe's "Sampling Function Builder". This would allow the modeller (the researcher) to appropriately identify and enter the parameters into EZStrobe. Table 7.7 presents the differences between the parameters of EZStrobe's and EasyFit's distribution functions. However, the modeller (the researcher) was able to recognise the required parameters and where they needed to be entered in EZStrobe's "Sampling Function Builder" option.

Table 7.7 Parameters of probability distribution function (PDF) in EZStrobe and EasyFit

Probability distribution	EZStrobe parameters	EasyFit parameters	EZStrobe parameters	EasyFit parameters	EZStrobe parameters	EasyFit parameters
Normal	Mean	μ	St.Dev.	σ		
Beta	Alpha	a	Beta	b		
Exponential	Mean	μ				
PERT	P0	a	Mode	M	P100	b
Triangular	Low	a	Mode	m	High	b
Uniform	Low	Low	High	High		
Gamma	α	α	β	β		
Erlang	Order	Beta	Mean	m		

As Table 7.7 shows, the resulting parameters from EasyFit are different to what has been designed in EZStrobe's "Sampling Function Builder". For example, in the Erlang distribution, the parameters are "Order" and "Mean" in EZStrobe whereas in EasyFit, they are shown as "Mean" and "m", respectively. Therefore, the required parameters have been translated as presented in Table 7.8.

Table 7.8 Translation of probability distribution function (PDF) results from EasyFit to EZStrobe

EasyFit output	EZStrobe input
Beta [a, b]	Beta [α, β]
Gamma [α, β]	Gamma [α, β]
PERT [a, M, b]	PERT [P0, Mode, P100]
Normal [μ, σ]	Normal [Mean, Std. Dev.]
Triangular [a, m, b]	Triangular [Low, Mode, High]

The results of the fit distribution are summarised in Table 7.9. The last column on this table comprises the input parameters entered into the "Sampling Function Builder" window in EZStrobe.

Table 7.9 Information on Activities included in developed model

First Data Set					
Activity number	**Activity name**	**Types of node**	**Selected best fit distribution**	**Distribution parameters (EasyFit output)**	**EZStrobe input**
Ac.1	BeamRdyToPick	Combi	Gamma	α=22.425, β=1.2007	Gamma [22.425, 1.2007]
Ac.2	UnlddTrckLeaves	Normal	Gamma	α=31.792, β=0.32477	Gamma [31.792, 0.32477]
Ac.3	PlcbmToGround	Combi	Normal	μ=8.475, σ=1.987	Normal [8.475, 1.987]
Ac.4	FnshPlcGround	Normal	Normal	μ=5.05, σ=0.71432	Normal [5.05, 0.71432]
Ac.5	Preparation	Combi	Normal	μ=28.325, σ=4.6871	Normal [28.325, 4.6871]

First Data Set					
Activity number	**Activity name**	**Types of node**	**Selected best fit distribution**	**Distribution parameters (EasyFit output)**	**EZStrobe input**
Ac.7	LftngUpPrprdBm	Combi	Gamma	α=44.874, β=0.23065	Gamma [44.874, 0.23065]
Ac.8	FinishHangngBm	Normal	Normal	μ=9.3, σ=2.0531	Normal [9.3, 2.0531]
Ac.9	BmRdyLnch	Combi	Erlang or Gamma	Erlang: m=22. β=0.48288 Gamma: α=22.211. β=0.48288	Gamma [22.211, 0.48288]
Ac.11	GntCrnStartLnch	Normal	Gamma	α=12.961, β=0.76768	Gamma [12.961, 0.76768]
Ac.10	BmMvDwn	Combi	Normal	σ=3.8377, μ=20.125	Normal [20.125, 3.8377]
Ac.12	FnshPlcmnt	Normal	Beta or Normal	Beta: a=10.558, b=57.534 Normal: σ=5.518, μ=31.25	Normal [31.25, 5.518]
Ac.13	GntryMveUp	Normal	Gamma	α=17.617, β=0.54209	Gamma [17.617, 0.54209]
Ac.14	GntryRdyBck	Normal	Gamma	α=25.472, β=0.40828	Gamma [25.472, 0.40828]
Ac.15	GntryPushBck	Normal	PERT Triangular	PERT [a, M, b]= [0.20671, 17.416, 25.799] Triangular [a, m, b]= [2.9193, 20.0, 25.549]	Triangular [2.9193, 20.0, 25.549]
Ac.16	FinishLocking	Combi	Gamma	α=7.7452, β=0.90056	Gamma [7.7452, 0.90056]

7.1.4 RUNNING EZSTROBE

In contrast to the previous model where simulation used the non-distribution functions based on the durations of Activities, in the model developed here, the functions computed by EasyFit were added to the model. EZStrobe was then run and the output was ready for interpretation. The results of EZStrobe for Queues and Activities are presented in Tables 7.10 and 7.11, and explained in detail in Table 7.12. Validation and verification of the current model were then completed with these results presented in the next section.

Table 7.10 Simulation output: Results for Queues

Ac.	Queue	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
1	BmRdyFrPlc	0.00	1.00	0.00	0.00	0.00	0.00	1.00
2	BmRdyFrPrprtn	0.00	1.00	0.00	0.00	0.00	0.00	1.00
3	BmRdyOnTpofSpn	0.00	1.00	0.00	0.00	0.00	0.00	1.00
4	BmRdyToBHung	0.00	1.00	0.00	0.00	0.00	0.00	1.00
5	Crew1	3.00	6.00	0.00	0.00	0.00	0.00	3.00
6	Crew1RdyLnch	0.00	3.00	5.00	0.14	0.62	0.00	3.00
7	Crew1Ready	3.00	12.0	18.75	2.04	1.40	0.00	3.00
8	Crew2	2.00	4.00	0.00	0.00	0.00	0.00	2.00
9	Crew2Rdy	2.00	6.00	30.11	1.64	0.77	0.00	2.00
10	Crew2Ready	2.00	8.00	18.75	1.36	0.93	0.00	2.00
11	Crew3	2.00	4.00	0.00	0.00	0.00	0.00	2.00
12	Crew3Rdy	2.00	6.00	30.11	1.64	0.77	0.00	2.00
13	Crew3Ready	2.00	8.00	18.75	1.36	0.93	0.00	2.00
14	Crew4Rdy	2.00	6.00	26.78	1.46	0.89	0.00	2.00
15	GntcrnRdy	1.00	2.00	0.00	0.00	0.00	0.00	1.00
16	GntryRdyLock	0.00	1.00	0.00	0.00	0.00	0.00	1.00
17	LddTrckIdle	0.00	1.00	0.00	0.00	0.00	0.00	1.00

Table 7.11 Simulation output: Results for Activities

Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur	MinDur	MaxDur	AvInt	SDInt	MinInt	MaxInt
BeamRdyToPick	0	1	0.00	0.00	22.93		22.93	22.93				
BmMvDwn	0	1	112.74	112.74	24.02		24.02	24.02				
BmRdyLnch	0	1	94.08	94.08	10.15		10.15	10.15				
End	0	1	190.35	190.35	0.00		0.00	0.00				
FinishHangngBm	0	1	83.80	83.80	10.28		10.28	10.28				
FinishLocking	0	1	184.06	184.06	6.29		6.29	6.29				
FinishPrpartn	0	1	73.76	73.76	0.00		0.00	0.00				
FnshPlcGrnd	0	1	34.72	34.72	5.04		5.04	5.04				
FnshPlcmnt	0	1	136.76	136.76	24.40		24.40	24.40				
GntCrnStartLnch	0	1	104.24	104.24	8.50		8.50	8.50				
GntryMveUp	0	1	136.76	136.76	10.47		10.47	10.47				
GntryPushBck	0	1	160.60	160.60	23.46		23.46	23.46				
GntryRdyBck	0	1	147.23	147.23	13.36		13.36	13.36				
LftngUpPrprdBm	0	1	73.76	73.76	10.04		10.04	10.04				
PlcBmToGround	0	1	22.93	22.93	11.79		11.79	11.79				
Preparation	0	1	39.76	39.76	34.00		34.00	34.00				
UnlddTrckLeavs	0	1	22.93	22.93	11.84		11.84	11.84				
					226.57							

No outputs were computed for this parameter in this model.

7.1.5 VERIFICATION AND VALIDATION OF GNRI STROBE MODEL I

The developed model's logic was checked against the logic of the fieldwork project, in a similar manner to the verification and validation phase explained in Section 6.7.1, and then through the interpretation of the outputs of the Queues and Activities. With the current model developed in three small parts, the modeller (the researcher) could undertake the interpretation and assessment in more detail. This provided the opportunity to interpret some of the simulation output with regard to the behaviour of the Queues or Activities in one small part rather than their behaviour in the whole system. However, the interpretation of the output presented in the following section may seem different to that in the previous sections.

Table 7.12 first presents the interpretation of the Cur results for Queues, taking into consideration the behaviour of Queues in the entire system. In Table 7.13, the Cur results are then analysed in accordance with the behaviour of Queues in each part of the model. In this way, the assessment of the Queues was double-checked to ensure that the modelled Queues were accurate.

Table 7.12 Assessing the model through interpretation of Cur results for Queues

Interpretation of Cur results for Queues				Comparison analysis
Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Does the developed model conform to the logic of the real-world project?
BmRdyFrPlc	0.00	The resource does not hold any content of the Beam type in the Ready state at the time of the report.	When Ac.1 is completed, the super T-beam delivered to the gantry crane is ready to be placed on the ground. The beam thus holds this Ready state until the unloaded truck leaves the gantry area and the gantry crane can move the beam down. However, by starting Ac.3, the beam no longer stays in the Ready state.	√
BmRdyFrPrprtn	0.00		By the completion of Ac.4, the super T-beam that is already placed on the ground should be prepared for the launching operation. Therefore, the beam holds this state to allow Ac.5 to receive all of its required resources and to begin. By the commencement of Ac.5, this resource changes state, and the beam in this state is no longer available in the system.	√
BmRdyOnTpofSpn	0.00		By the completion of Ac.10, the loaded gantry crane stops over the span where the super T-beam is to be placed. At this time, the beam is on the gantry crane and is in the Ready state for being placed on its supports. The beam stays in this state until all of the required conditions for the commencement of Ac.11 are ready. After Ac.11 starts, the state of the beam changes as the Activity involves moving down to the support, and then the beam being placed in its final position.	√
BmRdyToBHun**g**	0.00		After the completion of Ac.4, the super T-beam is ready for its preparation for the launching operation. By the completion of Ac.6, the state of the beam changes to being in the Ready state for being lifted up by the gantry crane. The beam stays in this state until the required resources for the commencement of Ac.7 become ready. Later on, the beam does not stay in this state in the system.	√
Crew1	3.00		After the completion of Ac.10, Crew 1, which has been in the Ready state for launching, switches to the new state. In the current state, Crew 1 is involved in the accomplishment of Ac.11. Later, the crew is busy with the completion of its next tasks until the time when the gantry crane is returned to the auxiliary support and locked. Therefore, Crew 1 with its assigned number of resource units holds the same state right to the end of the operation.	√
Crew1RdyLnch	0.00		As explained above, by the completion of Ac.10, Crew 1 should enter the Ready state for launching the loaded gantry crane toward the considered	√

Interpretation of Cur results for Queues				Comparison analysis
Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Does the developed model conform to the logic of the real-world project?
			span. The crew stays in this state until Ac.9 receives all of its required resources and begins. Later on, Crew 1 in the same state is no longer in the system.	
Crew1Ready	3.00	The computed Cur shows that Crew 1 at the report time contains 3 resource units. With the model developed as a closed loop, the logic of the developed model conforms to the concept of the real-world project. However, after the completion of each round of operation, Crew 1 switches state from that shown as "Crew 1" to "Crew 1 Ready".	At the start of the operation (time 0), Crew 1 should be ready to deliver the super T-beam from the truck to the gantry crane. This crew stays in the same state until Ac.5 is completed. This crew would no longer hold the same state unless the operation was considered as a loop in which, at the end of each round, the next round would start.	√
Crew2	2.00		Similar to Crew1	√
Crew2Rdy	2.00	With the model developed as a closed loop, it is acceptable that this crew holds the assigned content at SimTime.	By completion of Ac.6, Crew 2 should be in the Ready state for lifting up the prepared super T-beam to the gantry crane. The crew stays in this state until Ac.9 is completed.	√
Crew2Ready	2.00		Similar to Crew1Ready	√
Crew3	2.00		Similar to Crew1	√
Crew3Rdy	2.00		Similar to Crew2Rdy	√
Crew3Ready	2.00		Similar to Crew1Ready	√
Crew4Rdy	2.00	As explained for Crew2Rdy, the computed Cur for this crew is also acceptable.	By completion of Ac.12, Crew 4 joins the operation. This crew helps with moving the loaded gantry crane down to the support, and finishing the placement of the super T-beam on the support. This crew also participates in starting Ac.16, and holds the Ready state until the operation finishes.	√

Interpretation of Cur results for Queues				Comparison analysis
Queue	Cur	Interpretations according to simulation output	Interpretations according to fieldwork project	Does the developed model conform to the logic of the real-world project?
GntcrnRdy	1.00		Similar to Crew1Ready	√
GntryRdyLock	0.00		By completion of Ac.15, the unloaded gantry crane is ready to be locked at the auxiliary support. By starting Ac.16, this resource no longer holds the same state in the system.	√
LddTrckIdle	0.00		At time 0 when the operation starts, a loaded truck is required to be in the gantry area. The availability of a loaded truck in the gantry area is one of the required conditions for starting Ac.1. This resource is not available after Ac.1 is completed.	√

As explained in Section 6.7.1, another way to check the accuracy of Cur quantities is to assess the total number of crews assigned to each small part of the current model. The computed Cur for crew Queues for each of the three small parts is summarised in Table 7.13. The comparison between what has been assigned and what is presented in the matrix analysis (Figure 7.1) illustrates the accuracy of the Cur results for Queues in this model (see Table 7.13).

Table 7.13 Summary of Cur results in different parts of system

Part number of the system	Queue	Current content	Total Cur content
Part 1	Crew1Ready	3.00	
Part 1	Crew2Ready	2.00	7
Part 1	Crew3Ready	2.00	
Part 2	Crew1RdyLnch	0.00	
Part 2	Crew2Rdy	2.00	4
Part 2	Crew3Rdy	2.00	
Part 3	Crew2	2.00	
Part 3	Crew1	3.00	9
Part 3	Crew3	2.00	
Part 3	Crew4Rdy	2.00	

In Table 7.14, the Tot results for Queues are interpreted and compared to the logic of the real-world fieldwork operation. Where the logic of the developed model conforms to the real-world project's concept, a "√" has been included in the table's last column.

Table 7.14 Assessing the model through interpretation of Tot results for Queues

Interpretation of results of computed Tot at SimTime for Queues				
Queue	Tot	Maximum amount of resources assigned	Does the model conform to the concept of the real-world project according to Tot?	Accepting or rejecting?
BmRdyFrPlc	1.00	1	At the completion of Ac.1, the super T-beam is loaded onto the gantry crane, and is in the Ready state to be placed on the ground. The availability of this resource is one of the required conditions for Ac.3. Otherwise, the operation cannot proceed to the next steps. This Queue with this state is only involved in performing Ac.3. Thus, the total number of resource units that enter this Queue is 1.	√
BmRdyFrPrprtn	1.00	1	When the beam is placed on the ground, this means that one super T-beam is available on the ground for performing the preparation task. Therefore, the total number of resource units that enter this Queue is 1.	√
BmRdyOnTpofSpn	1.00	1	After launching the loaded gantry crane to the top of the span, where the super T-beam is to be placed, the crane should stop and allow the crews to change their states. The availability of the beam at the top of the span is one of the required conditions for the commencement of Ac.11. This Queue needs to be in the Ready state for the completion of only one task (Ac.11). Therefore, the total number of resource units that enter this Queue is 1.	√
BmRdyToBHung	1.00	1	At the completion of Ac.6, the prepared super T-beam is in the Ready state to be loaded onto the gantry crane. This Queue meets the requirements for only one Activity (Ac.7). Therefore, the total number of resource units that enter this Queue is 1.	√
Crew1	6.00	3	When Ac.10 is completed, the crews should be in another Ready state to proceed to the placement of the super T-beam onto its support. Later, when the whole operation is completed, the crews become available for the next round of the operation. As the computed Tot also shows, two time resource units associated with this Queue have entered the Queue.	√
Crew1RdyLnch	3.00	3	At the completion of Ac.7, Crew 1 should change to the Ready state for the launching operation. The availability of Crew 1 is one of the required conditions for the commencement of Ac.9. Therefore, the total number of resource units that enter this state is 3.	√
Crew1Ready	12.0	3	Early in the operation, one of the required conditions for the commencement of Ac.1 is the availability of 3 persons in Crew 1. This crew in the same Ready state also participates in the completion of Ac.3 and Ac.4. Therefore, the total number of resource units that enter this Queue is 12. The first time is when the operation starts with 3 units available in this Queue; the second time is at the completion of Ac.1 when Crew 1 is getting ready for the completion of Ac.3; and the third time is at the completion of Ac.3, when the crew is getting ready to start	√

Interpretation of results of computed Tot at SimTime for Queues				
Queue	Tot	Maximum amount of resources assigned	Does the model conform to the concept of the real-world project according to Tot?	Accepting or rejecting?
			Ac.4.	
Crew2	4.00	2	When Ac.10 is completed, the crews should be in the Ready state to proceed to the placement of the super T-beam onto its support. Later, when the whole operation is completed, the crews become available for the next round of the operation. As the computed Tot also shows, two time resource units associated with this Queue have entered the Queue.	√
Crew2Rdy	6.00	2	At the completion of Part 1 of the operation, the super T-beam preparation, Crew 2 should be in the Ready state for starting the launching operation. The first step for the launching operation is the gantry crane lifting up the prepared beam. Therefore, the availability of resources in this Queue is one of the required conditions for the commencement of that Activity (Ac.7). By the completion of Ac.8, the resource units associated with Crew 2 should be in the Ready state for the launching operation. There are then 3 times that this crew in the same state is available in the system: 1) to commence Ac.7; 2) when Ac.8 is completed; and 3) to commence Ac.9.	√
Crew2Ready	8.00	2	Early in the operation, one of the required conditions for the commencement of Ac.1 is the availability of 2 persons in Crew 2. This crew in the same Ready state also participates in the completion of Ac.3 and Ac.4. Therefore, the total number of resource units that enter this Queue is 12. At the first time, 2 units are available in this Queue when the operation starts; at the second time when Ac.1 is completed, Crew 2 gets ready for the completion of Ac.3; and at the third time, with the completion of Ac.3, the crew gets ready to start Ac.4.	√
Crew3	4.00	2	When Ac.10 is completed, the crews should be in the Ready state to proceed to the placement of the super T-beam onto its support. Later, when the whole operation is completed, the crews become available for the next round of the operation. As the computed Tot also shows, two time resource units associated with this Queue have entered the Queue.	√
Crew3Rdy	6.00	2	Similar to what has been explained for Crew2Rdy	√
Crew3Ready	8.00	2	Similar to what has been explained for Crew2Ready	√
Crew4Rdy	6.00	2	In order to start Ac.11, 2 more persons who are available as Crew 4 are the requirement. This crew also participates in the completion of Ac.16. Firstly, they participate in moving the loaded gantry crane downward to the support, and then they finish the placement of the super T-beam (Ac.12). By the completion of Ac.12, Crew 4 should be available to start Ac.16. Therefore, the 2 persons in Crew 4 should play this role 3 times.	√

Interpretation of results of computed Tot at SimTime for Queues				
Queue	Tot	Maximum amount of resources assigned	Does the model conform to the concept of the real-world project according to Tot?	Accepting or rejecting?
GntcrnRdy	2.00	1	At the start of the operation, the gantry crane should be in the Ready state for delivering the super T-beam from the truck. Each time the operation is completed, the assumption is that the next beam is available. Therefore, the first beam is available once to start the operation and, at the end of the operation when the gantry crane is locked at auxiliary support, the next beam enters the process.	√
GntryRdyLock	1.00	1	At the end of the operation, the gantry crane should be properly locked so the next round of the operation can start on the same day or the next day. Thus, in total, the gantry crane enters this state once per round of operation.	√
LddTrckIdle	1.00	1	At the starting point of the operation, the availability of the truck loaded with one super T-beam is one of the required conditions not only for the commencement of Ac.1, but for the commencement of the entire operation.	√

The verification and validation phase was continued by interpretation and comparison analysis of the simulation output for the Activities. The results are included in Tables 7.15–7.17.

Table 7.15 Assessing the model through interpretation of Tot results for Activities

Activity	Tot	Interpretations	Accepting or rejecting?
BeamRdyToPick	1	As shown in the computed results, all Activities were completed once in the developed model designed for one round of operation. Referring to previous discussions (Section 7.15), all Activities were modelled in such a way that the model conforms to the logic of the real-world project.	√
BmMvDwn	1		
BmRdyLnch	1		
End	1		
FinishHangngBm	1		
FinishLocking	1		
FinishPrpartn	1		
FnshPlcGrnd	1		
FnshPlcmnt	1		
GntCrnStartLnch	1		
GntryMveUp	1		
GntryPushBck	1		
GntryRdyBck	1		
LftngUpPrprdBm	1		
PlcBmToGround	1		
Preparation	1		
UnlddTrckLeavs	1		

Table 7.16 Assessing the model through interpretation of 1st and last SimTime results for Activities

Activity	1Stst	LstSt	Interpretations	Accepting or rejecting?
BeamRdyToPick	0.00	0.00	The computed 1stSt is equal to the computed LstSt. Therefore, the current model meets this criterion.	√
BmMvDwn	112.74	112.74		
BmRdyLnch	94.08	94.08		
End	190.35	190.35		
FinishHangngBm	83.80	83.80		
FinishLocking	184.06	184.06		
FinishPrpartn	73.76	73.76		
FnshPlcGrnd	34.72	34.72		
FnshPlcmnt	136.76	136.76		

Activity	1Stst	LstSt	Interpretations	Accepting or rejecting?
GntCrnStartLnch	104.24	104.24		
GntryMveUp	136.76	136.76		
GntryPushBck	160.60	160.60		
GntryRdyBck	147.23	147.23		
LftngUpPrprdBm	73.76	73.76		
PlcBmToGround	22.93	22.93		
Preparation	39.76	39.76		
UnlddTrckLeavs	22.93	22.93		

Table 7.17 Assessing the model through interpretation of 1st SimTime results for Activities

Activity	**1stSt**	**Sequence according to 1stSt**	**Interpretations**	**Accepting or rejecting?**
BeamRdyToPick	0.00	1	The results match the real-world operation.	√
BmMvDwn	112.74	11		
BmRdyLnch	94.08	9		
End	190.35	17		
FinishHangngBm	83.80	8		
FinishLocking	184.06	16		
FinishPrpartn	73.76	6		
FnshPlcGrnd	34.72	4		
FnshPlcmnt	136.76	12		
GntCrnStartLnch	104.24	10		
GntryMveUp	136.76	13		
GntryPushBck	160.60	15		
GntryRdyBck	147.23	14		
LftngUpPrprdBm	73.76	7		
PlcBmToGround	22.93	3		
Preparation	39.76	5		
UnlddTrckLeavs	22.93	2		

The model output showed that the concept of the model matched the logic of the operation in the studied case project. Therefore, the last model was selected as the foundation for further exploration of the capabilities of EZStrobe, with this study calling the simulated model, the “GNRI Strobe Model I”.

In the next step, firstly, the framework for the development of the simulation model was developed and discussed. The capabilities of the EZStrobe program, in terms of the “Probabilistic Branch” function and ‘what if’ scenarios, then underwent experimentation which is presented in the next section.

7.2 DEVELOPING A FRAMEWORK FOR THE USE OF EZSTROBE IN SIMULATING A CONSTRUCTION OPERATION

The procedure followed by the current study from the preliminary study to the stage where the GNRI Strobe Model I was achieved led the study to construct a framework which is presented in Figure 7.3.

As mentioned before, the EZStrobe program, as experienced by the current study, indicated the need to improve the modelling procedure, a point which has been suggested in previous studies (see Section 6.3). The steps discussed in Section 6.3 are also included in the developed framework in Figure 7.3 in a text box within a text box presented with a dashed line border. Therefore, the current developed framework is able to present the extra details and/or steps which should proceed to achieve a successful EZStrobe model.

According to the developed framework, a modelling procedure starts by collecting the data. In the case where the modeller is dealing with a new operation, a good understanding of the system behaviour is crucial for the development of a successful conceptual model. At this step, the modeller could use document analysis aligned with observation and note taking in a fieldwork study. The collected data should be organised in line with the questions included in the next step. The development of a framework and/or flow chart should be started so the modelling procedure is conducted through a better understanding of the system behaviour, thus initiating the translation of the conceptual model into the EZStrobe program. An understanding of the operation also helps in the formulation of assumptions, with these used later within the phase in which the model undergoes verification and validation. These assumptions should be clearly formulated to allow the modeller to evaluate the accuracy of the model in the next steps. Before carrying out the model development using EZStrobe standards, the modeller should ensure that the interdependencies between different parts of the operation are understood. The interactions between the system elements are going to be formulated in the EZStrobe model by drawing a released link or a feeding link, etc.;

therefore, analysing the interdependencies will help with applying more appropriate logic in the model under development.

In the current study, the modelling procedure followed Steps 3 and 4, as explained in Section 6.3, to prepare an EZStrobe ACD with annotations showing the Queues and Activities and the amount and content of resources that flowed through the arrow links. In drafting the ACD model, the modeller can then complete the fit distribution analysis to estimate the duration for all Activities (Step 5 as discussed in Section 6.3). The best distribution function resulting from analysis with the EasyFit software should then be entered in EZStrobe's "Sampling Function Builder". At this time, the model is ready to be run. The procedure can go through analysis and interpretation of the outcome and, consequently, assessment of the assumptions formulated in previous steps. Some important criteria should be checked by answering the following questions:

1- Does the total duration match the life cycle of the real-world project?
2- Does the number of resources match the content of resources in the real-world project?
3- Does the simulation finish owing to lack of resources?
4- Do the sequence of Activities and interactions between Activities and resources conform to the concept of the real-world project?

If all these criteria are met, the modeller can then start expansion of the model by parameterising, further exploring the capabilities of EZStrobe and undertaking 'what if' scenario analysis. In the case where the model is run using "No Sampling Function Builder", the model should be revised by entering the duration of the Activity using the "Sampling Function Builder". It needs to be highlighted that, at the last step, in order to enhance the validity of the model, the simulated model should be normalised by adding another data set. (For example, in the current study, the 54 more data sets collected on the construction of Ramp 4 were added to the simulated model to normalise the GNRI Strobe Model I (see Section 7.4).

If any of the above criteria are not met, the model concept needs to be totally revised. The modeller could break down the system and again follow the steps from formulating the assumptions onwards.

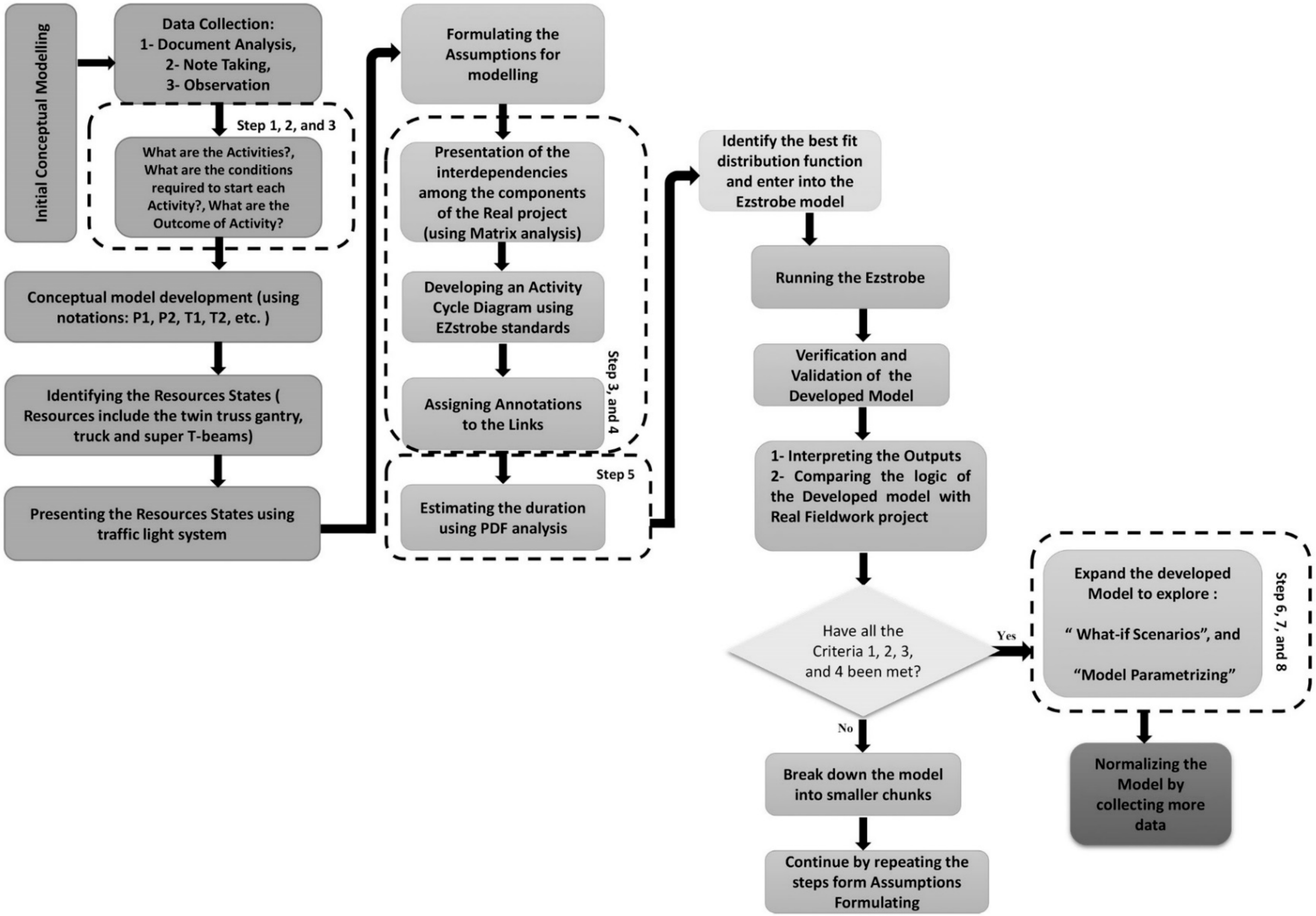


Figure 7.3 Framework for implementation of EZStrobe in simulating a construction operation

As the current research achieved the model (GNRI Strobe Model I) which met all the above criteria, the next step was for the research to explore the capabilities of EZStrobe with the purpose of achieving its objectives.

7.3 EXPLORING THE CAPABILITIES OF EZSTROBE

After the framework was developed for the use of EZStrobe in the case study project, the research next examined the capabilities of EZStrobe in terms of the modelling of different scenarios and its “Animation” capability to gain a better insight into the system behaviour. ‘What if’ scenarios were modelled using the “Probabilistic Branch” function, and estimating the duration of the operation was modelled using EZStrobe’s “Parameterizing and Results” options. Moreover, other scenarios which were experienced in the fieldwork were modelled and discussed to illustrate the effect of different constraints on the duration of the studied operation.

7.3.1 INSERTING THE “PROBABILISTIC BRANCH” (“FORK” ELEMENT)

EZStrobe can probabilistically select one among several successors to an Activity for resource routing and activation. This is achieved with a “Fork” and the “Branch Links” that emanate from it (Martinez, 2001).

A Fork is a probabilistic routing element which typically follows an Activity but can also follow another Fork. When the instance of a preceding Activity finishes, a Fork then chooses one of its successors. If the chosen successor is a Bound Activity, then the Bound Activity starts. If the chosen successor is a Queue, then the Queue receives any resources routed through the Fork. If the chosen successor is another Fork, then the second Fork will choose one of its successors. The relative likelihood that a particular successor will be chosen depends on the “P” property of the Branch Link that emanates from the Fork towards the successor.

According to the description of the case study project (see Section 6.1), this Fork element could be applied to where the procedure for the placement of the edge beam should be modelled. Two scenarios for the launching and placement of the edge beam were simulated to explore how this modelling element in EZStrobe could bring a better insight into the process for the managers and planners. These two scenarios are described and presented in the next two sections.

7.3.1.1 Scenario I: Launching and Placement of the Edge Beam in Bridge Operation

To simulate the bridge operation undertaken when the launching and placement of an edge beam are in progress, a new part was added to the previous model which is presented within the brown circle (Figure 7.2). In accordance with the bridge structure, Span 7 comprises five beams, two of which are edge beams. Therefore, the probability of proceeding with the procedure for the placement of intermediate beams and edge beams is P(3/5)=60% and P(2/5)=40%, respectively. As shown in the developed model in Figure 7.2, two additional elements have been added to the last developed model to present the pathway which should be followed when the operation intends to place an edge beam. These two elements are:

1- A Queue that is annotated as EdgeClmpsRdy and
2- A Combi that is annotated as EdgeClampsInstl. Data collected in the fieldwork operation showed that the duration for this Combi was almost 20 minutes.

However, the cycle time for this model became longer than what had been estimated for the previous model (see Section 7.4, Figure 7.2). As explained in the previous model (Figure 7.2), the real cycle time varied between 213.75 minutes and 303 minutes (see Table 7.3). Therefore, in this model, when taking into consideration the 20 minutes' extra duration for the completion of Ac.5, the cycle time could vary between 244 minutes and 323 minutes.

The sequence of Activities in the real-world project are presented in Table 7.18. As explained above, the probability of the accomplishment of Ac.5 is 40%. Therefore, the intention of this model was to present the extent to which the simulation output (e.g. cycle time and interactions between the model elements) would differ from the results in the last model. This model's output is described in the next section.

Table 7.18 Information on Activities and their sequence in Model Extension I

Activity	Sequence according to fieldwork operation
BeamRdyToPick	Ac.1
UnlddTrckLeavs	Ac.2
PlcBmToGround	Ac.3
FnshPlcGrnd	Ac.4
EdgeClampsInstl	Ac.5
Preparation	Ac.6
FinishPrpartn	Ac.7
LftngUpPrprdBm	Ac.8
FinishHangngBm	Ac.9
BmRdyLnch	Ac.10
GntCrnStartLnch	Ac.11
BmMvDwn	Ac.12
FnshPlcmnt	Ac.13
GntryMveUp	Ac.14
GntryRdyBck	Ac.15
GntryPushBck	Ac.16
FinishLocking	Ac.17
End	Ac.18

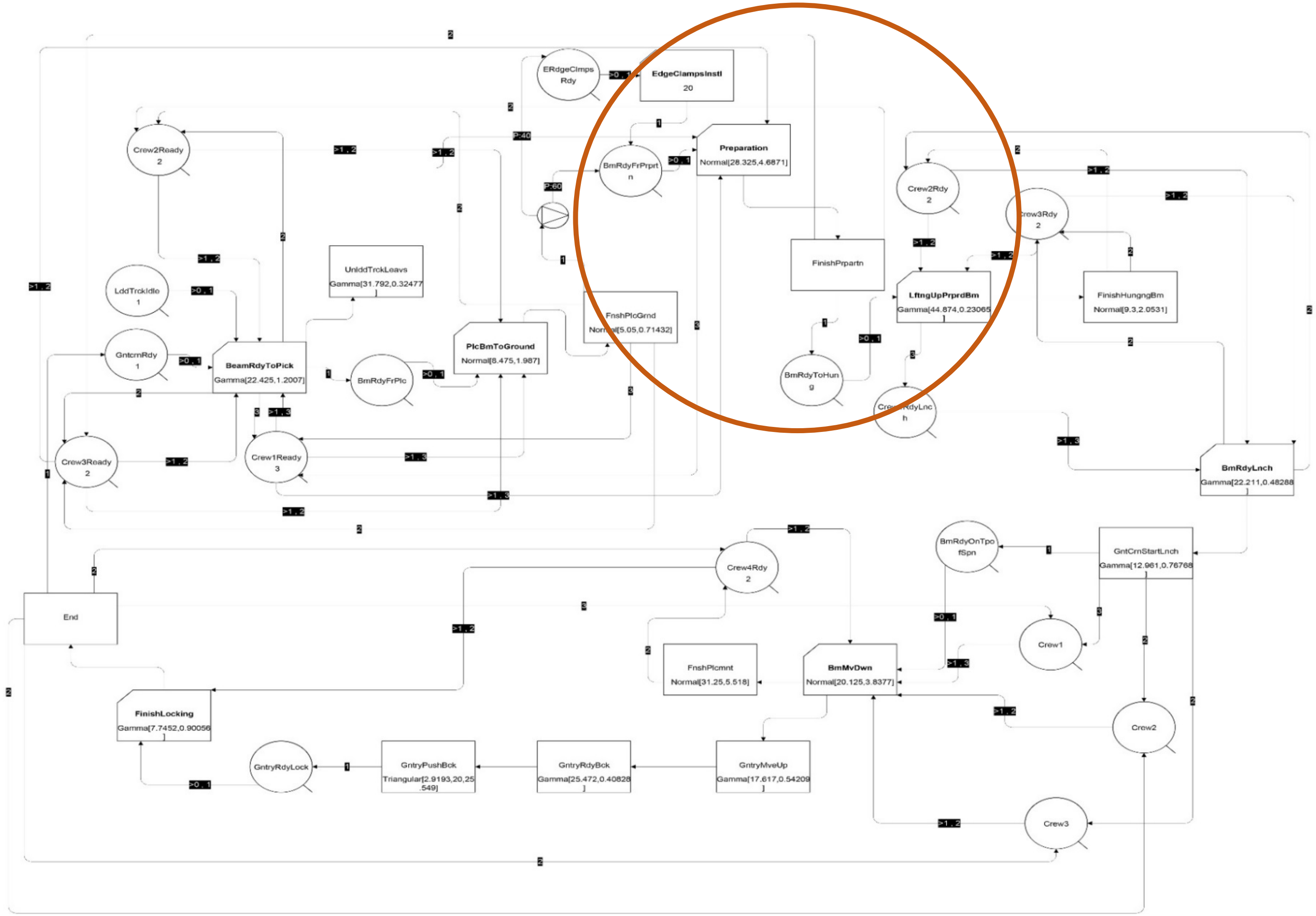


Figure 7.4 Simulating delivery of edge beam in bridge launching operation (using "Probabilistic Branch" function)

The output of Queues and Activities that resulted from the simulation of the developed model (Figure 7.4) are summarised in Tables 7.19 and 7.20.

Table 7.19 Queues' output

Ac.	Queue	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
1	BmRdyFrPlc	0	1	0	0	0	0	1
2	BmRdyFrPrprtn	0	1	0	0	0	0	1
3	BmRdyOnTpofSpn	0	1	0	0	0	0	1
4	BmRdyToBHung	0	1	0	0	0	0	1
5	Crew1	3	6	0	0	0	0	3
6	Crew1RdyLnch	0	3	6.93	0.1	0.55	0	3
7	Crew1Ready	3	12	30.26	1.83	1.46	0	3
8	Crew2	2	4	0	0	0	0	2
9	Crew2Rdy	2	6	56.58	1.71	0.7	0	2
10	Crew2Ready	2	8	30.26	1.22	0.98	0	2
11	Crew3	2	4	0	0	0	0	2
12	Crew3Rdy	2	6	56.58	1.71	0.7	0	2
13	Crew3Ready	2	8	30.26	1.22	0.98	0	2
14	Crew4Rdy	2	6	46.34	1.4	0.92	0	2
15	EdgeClmpsRdy	0	1	0	0	0	0	1
16	GntcrnRdy	1	2	0	0	0	0	1
17	GntryRdyLock	0	1	1.61	0.01	0.09	0	1
18	LddTrckIdle	0	1	0	0	0	0	1

Table 7.20 Activities' output

Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur	MinDur	MaxDur	AvInt	SDInt	MinInt	MaxInt
BeamRdyToPick	0	1	0	0	22.93		22.93	22.93				
BmMvDwn	0	1	139.03	139.03	15.7		15.7	15.7				
BmRdyLnch	0	1	116.67	116.67	8.98		8.98	8.98				
EdgeClampsInstl	0	1	39.76	39.76	20		20	20				
End	0	1	198.21	198.21	0		0	0				
FinishHangngBm	0	1	109.74	109.74	6.93		6.93	6.93				
FinishLocking	0	1	189.94	189.94	8.27		8.27	8.27				
FinishPrpartn	0	1	97.18	97.18	0		0	0				
FnshPlcGrnd	0	1	34.72	34.72	5.04		5.04	5.04				
FnshPlcmnt	0	1	154.73	154.73	35.2		35.2	35.2				
GntCrnStartLnch	0	1	125.66	125.66	13.38		13.38	13.38				
GntryMveUp	0	1	154.73	154.73	8.24		8.24	8.24				
GntryPushBck	0	1	172.94	172.94	15.39		15.39	15.39				
GntryRdyBck	0	1	162.97	162.97	9.96		9.96	9.96				
LftngUpPrprdBm	0	1	97.18	97.18	12.56		12.56	12.56				
PlcBmToGround	0	1	22.93	22.93	11.79		11.79	11.79				
Preparation	0	1	59.76	59.76	37.42		37.42	37.42				
UnlddTrckLeavs	0	1	22.93	22.93	11.84		11.84	11.84				
					243.63							

As with the interpretation step completed in the model developed in Section 7.1.5 (see Figure 7.2), the above output was interpreted, and it was found that the logic of the model conformed to the concept of the real-world project. Comparing the output result for this model to that of the last model (Section 7.1), where no “Fork” element was included, showed how proceeding along the new pathway in the operation could influence the duration of the operation cycle. The cycle duration increased from 226 minutes to 244 minutes owing to the need for edge beam preparation.

7.3.1.2 Scenario II: From Temporary Placement to Permanent Placement of the Edge Beam in Bridge Launching Operation

As explained in subsection 7.3.1.1, the probability of having edge beams in a span that contains five beams is 40%. The construction method for the placement of this type of beam differs from that of the intermediate beams. Thus, the beam should first be placed in the middle of the span and then, by side shifting, it should be placed in its correct place. The new model was developed by extending the basic model (developed in Section 7.4) and applying the “Probabilistic Branch” function to explore how the cycle time differed. The required information about Activities and Queues included in this model is summarised in Table 7.21 and Table 7.22.

Table 7.21 Information on Activity (sequence and best fit distribution function)

Sequence	Activity	Duration
1	BeamRdyToPick	Gamma [22.425, 1.2007]
2	UnlddTrckLeavs	Gamma [31.792, 0.32477]
3	PlcBmToGround	Normal [8.475, 1.987]
4	FnshPlcGrnd	Normal [5.05, 0.71432]
5	Preparation	Normal [28.325, 4.6871]
6	FinishPrpartn	-------------
7	LftngUpPrprdBm	Gamma [44.874, 0.23065]
8	FinishHangngBm	Normal [9.3, 2.0531]
9	BmRdyLnch	Gamma [22.211, 0.48288]
10	GntCrnStartLnch	Gamma [12.961, 0.76768]
11	BmMvDwn	Normal [20.125, 3.8377]
12	PlconSuprt	25*
13	TmprPlcmnt	25*
14	SideShftng	20*
15	PrprSprtPrmntPl	20*
16	FnshPlcmnt	Normal [31.25, 5.518]
17	GntryMveUp	Gamma [17.617, 0.54209]
18	GntryRdyBck	Gamma [25.472, 0.40828]
19	GntryPushBck	Triangular [2.9193, 20, 25.549]
20	FinishLocking	Gamma [7.7452, 0.90056]
21	End	
*****The data for these Activities were obtained from the first experiment (on the placement and side shifting of the edge beam) in the fieldwork study. Therefore, their durations have been included in the model with no probability distribution function (PDF).		

Table 7.22 Information on Queues

Queue	Content
BeamAvailable	1
BmRdyFrPlc	1
BmRdyFrPrprtn	1
BmRdyOnTpofSpn	1
BmRdyPrmntPlcmn	1
BmRdyToBHung	1
BmRdyFrTmpPlcmn	1
C1PrmntPlc	3
C2PrmntPlc	2
C2TmpPlc	2
C3PrmntPlc	2
C3TmpPlc	2
C4PrmntPlc	2
Crew1	3
Crew1RdyLnch	3
Crew1Ready	3
Crew2	2
Crew2Rdy	2
Crew2Ready	2
Crew3	2
Crew3Rdy	2
Crew3Ready	3
Crew4Rdy	2
GntcrnRdy	1
GntryRdyLock	1

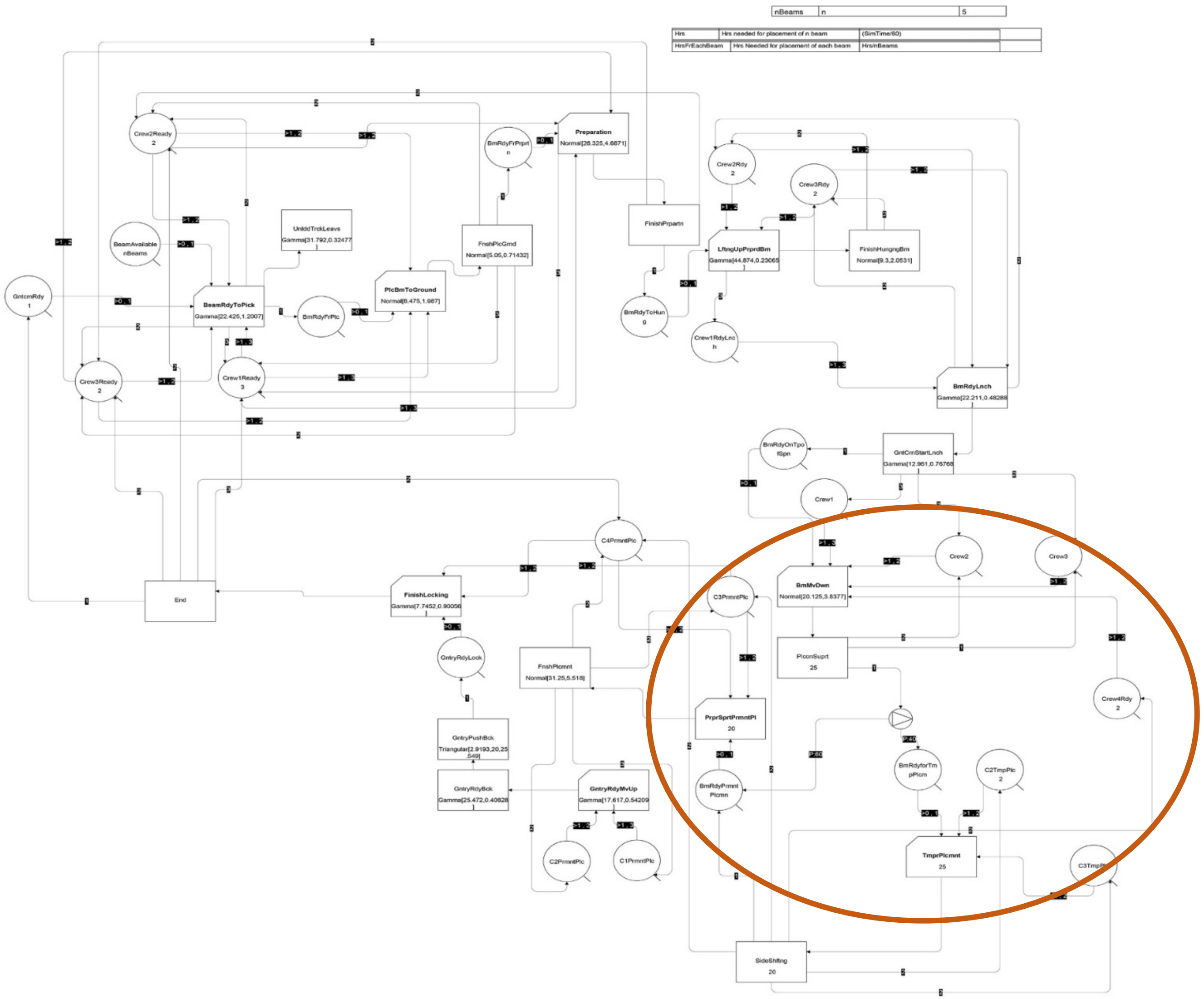


Figure 7.5 Simulating placement of edge beam in bridge launching operation

The model was run, with the simulation output results summarised in Tables 7.23 and 7.24.

Table 7.23 Simulation output results for Queues

Queue	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
BeamAvailable	1.00	5.00	545.60	2.71	1.02	1.00	5.00
BmRdyFrPlc	0.00	4.00	0.00	0.00	0.00	0.00	1.00
BmRdyFrPrprtn	0.00	4.00	0.00	0.00	0.00	0.00	1.00
BmRdyOnTpofSpn	0.00	4.00	0.00	0.00	0.00	0.00	1.00
BmRdyPrmntPlcmn	1.00	4.00	0.00	0.00	0.00	0.00	1.00
BmRdyToBHung	0.00	4.00	0.00	0.00	0.00	0.00	1.00
BmRdyFrTmpPlcmn	0.00	3.00	0.00	0.00	0.00	0.00	1.00
C1PrmntPlc	0.00	9.00	0.00	0.00	0.00	0.00	3.00
C2PrmntPlc	0.00	6.00	0.00	0.00	0.00	0.00	2.00
C2TmpPlc	2.00	8.00	217.53	1.73	0.68	0.00	2.00
C3PrmntPlc	0.00	12.00	15.22	0.18	0.57	0.00	2.00
C3TmpPlc	2.00	8.00	217.53	1.73	0.68	0.00	2.00
C4PrmntPlc	6.00	18.00	153.76	2.75	2.07	0.00	6.00
Crew1	0.00	12.00	0.00	0.00	0.00	0.00	3.00
Crew1RdyLnch	0.00	12.00	8.97	0.11	0.56	0.00	3.00
Crew1Ready	12.00	48.00	125.84	6.01	3.20	0.00	12.00
Crew2	8.00	16.00	210.02	3.34	2.07	0.00	8.00
Crew2Rdy	2.00	18.00	98.49	1.76	0.65	0.00	2.00
Crew2Ready	8.00	32.00	125.84	4.01	2.14	0.00	8.00
Crew3	4.00	12.00	140.01	1.67	1.04	0.00	5.00
Crew3Rdy	2.00	18.00	98.49	1.76	0.65	0.00	2.00
Crew3Ready	8.00	32.00	125.84	4.01	2.14	0.00	8.00
Crew4Rdy	0.00	8.00	174.54	1.39	0.92	0.00	2.00
GntcrnRdy	0.00	4.00	0.00	0.00	0.00	0.00	1.00
GntryRdyLock	0.00	3.00	0.00	0.00	0.00	0.00	1.00

Table 7.24 Simulation output results for Activities

Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur	MinDur	MaxDur	AvInt	SDInt	MinInt	MaxInt
BeamRdyToPick	0.00	4.00	0.00	866.67	27.48	4.23	22.93	32.81	288.89	8.74	279.61	296.98
BmMvDwn	0.00	4.00	112.74	968.35	17.99	5.00	11.78	24.02	285.20	13.95	274.24	300.91
BmRdyLnch	0.00	4.00	94.08	952.04	9.57	0.52	8.98	10.15	285.99	13.52	275.94	301.35
End	0.00	3.00	279.61	866.67	0.00	0.00	0.00	0.00	293.53	4.87	290.09	296.98
FinishHangngBm	0.00	4.00	83.80	942.82	8.97	1.69	6.51	10.28	286.34	10.14	279.71	298.01
FinishLocking	0.00	3.00	277.35	856.61	6.06	3.91	2.26	10.07	289.63	5.30	285.88	293.37
FinishPrpartn	0.00	4.00	73.76	931.87	0.00	0.00	0.00	0.00	286.04	11.46	277.45	299.05
FnshPlcGrnd	0.00	4.00	34.72	900.46	5.38	0.45	5.04	6.03	288.58	8.46	282.26	298.19
FnshPlcmnt	0.00	3.00	226.76	802.33	27.71	4.84	24.40	33.27	287.78	18.94	274.39	301.18
GntCrnStartLnch	0.00	4.00	104.24	961.02	10.64	3.21	7.33	13.83	285.59	14.25	275.14	301.82
GntryPushBck	0.00	3.00	270.07	847.77	10.37	4.08	7.28	15.00	288.85	4.52	285.65	292.05
GntryRdyBck	0.00	3.00	260.23	836.10	10.38	1.13	9.62	11.67	287.93	2.92	268.87	290.00
GntryMveUp	0.00	3.00	251.16	827.79	9.69	1.77	8.31	11.68	288.31	7.16	283.25	293.37
LftngUpPrprdBm	0.00	4.00	73.76	931.87	11.13	0.93	10.04	12.30	286.04	11.46	277.45	299.05
PlcBmToGround	0.00	4.00	22.93	892.29	8.63	2.48	5.77	11.79	289.79	9.97	282.89	301.22
PlconSuprt	0.00	4.00	136.76	980.13	25.00	0.00	25.00	25.00	281.12	17.68	267.81	301.18
Preparation	0.00	4.00	39.76	905.75	29.57	3.27	26.12	34.00	288.66	9.08	282.37	299.08
PrprSprtPrmntPl	0.00	3.00	206.76	782.33	20.00	0.00	20.00	20.00	287.78	18.94	274.39	301.18
SideShftng	0.00	3.00	186.76	762.33	20.00	0.00	20.00	20.00	287.78	18.94	274.39	301.18
TmprPlcmnt	0.00	3.00	161.76	737.33	25.00	0.00	25.00	25.00	287.78	18.94	274.39	301.18
UnlddTrckLeavs	0.00	4.00	22.93	892.29	10.70	1.78	8.55	12.45	289.79	9.97	282.89	301.22
					294.27							

As seen on Tables 7.23 and 7.24, when the edge beam placement was performed, the operation cycle time increased from 226 minutes (the result for the GNRI Strobe Model I in Section 7.1) to 294 minutes.

7.3.2 EXPLORING THE "ANIMATION" CAPABILITY

To explore the "Animation" capability of EZStrobe with simulation, the modeller (the researcher) selected a new scenario. For this scenario, data were collected on the placement of two beams, with assumptions formulated for a bridge operation with more than one instance. To run the STROBOSCOPE simulation on this model, the "Animation" mode in the STROBOSCOPE window (see Figure 7.6) was clicked on. Therefore, the current research could record a video of the animation, using the Camtasia® program. The video was later analysed with the relevant discussion presented in the following paragraphs.

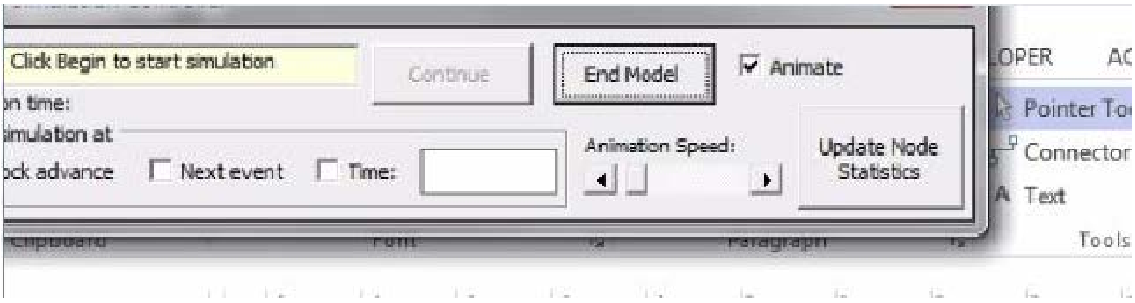


Figure 7.6 Setting "Animation" mode in EZStrobe environment

First, the following assumptions were formulated for the development of a model that comprised the placement of two beams:

1- The operation includes the placement of two beams. The number of instances of Activities in this model is more than 1.
2- The placement of two intermediate beams is included in this model.
3- The maximum content of resources is in accordance with the information presented in Table 7.26.
4- The interactions between resources and Activities, and the flow direction of resources should match the matrix analysis developed based on the real-world project (see Figure 7.1)
5- The sequence of the performance of Activities is according to the real-world project as presented in Table 7.25.

Table 7.25 Information on Activities and their sequence

Activity	Sequence according to fieldwork operation
BeamRdyToPick	Ac.1
UnlddTrckLeavs	Ac.2
PlcBmToGround	Ac.3
FnshPlcGrnd	Ac.4
Preparation	Ac.5
FinishPrpartn	Ac.6
LftngUpPrprdBm	Ac.7
FinishHangngBm	Ac.8
BmRdyLnch	Ac.9
GntCrnStartLnch	Ac.10
BmMvDwn	Ac.11
FnshPlcmnt	Ac.12
GntryMveUp	Ac.13
GntryRdyBck	Ac.14
GntryPushBck	Ac.15
FinishLocking	Ac.16
End	Ac.17

Table 7.26 Information on Queues and their content

Types of Resource	Resources	ACD model annotation	Assigned content
Human Resources (Gantry Crew)	Crew 1	Crew1Ready	3
		Crew1RdyLnch	3
		Crew1	3
	Crew 2	Crew2Ready	2
		Crew2Rdy	2
		Crew2	2
	Crew 3	Crew3Ready	2
		Crew3Rdy	2
		Crew3	2
	Crew 4	Crew4Rdy	2
Material	Super T-Beam	BeamAvailable	2
		BmRdyFrPlc	1
		BmRdyFrPrprtn	1
		BmRdyOnTpofSpn	1
		BmRdyToBHung	1
Machine	Crane	GntcrnRdy	1
		GntryRdyLock	1

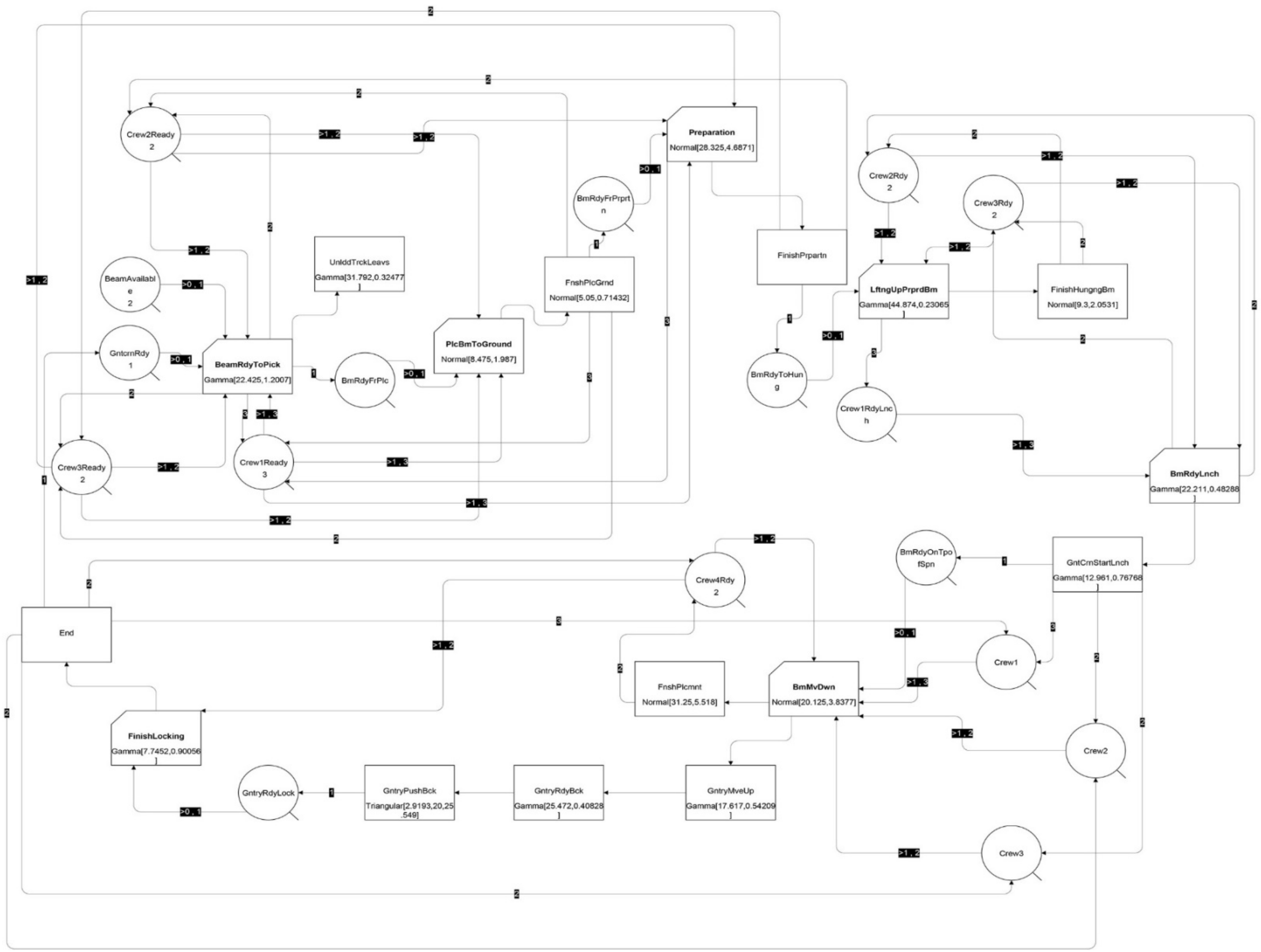


Figure 7.7 Simulation of GNRI gantry launching operation for placement of two beams

Tables 7.27 and 7.28 present the results from running the simulation of the model, as shown in Figure 7.7.

Table 7.27 Queues' output

Queue	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
BeamAvailable	0.00	2.00	95.17	0.55	0.50	0.00	2.00
BmRdyFrPlc	0.00	2.00	0.00	0.00	0.00	0.00	1.00
BmRdyFrPrprtn	0.00	2.00	0.00	0.00	0.00	0.00	1.00
BmRdyOnTpofSpn	0.00	2.00	0.00	0.00	0.00	0.00	1.00
BmRdyToBHung	0.00	2.00	0.00	0.00	0.00	0.00	1.00
Crew1	6.00	12.00	39.07	1.35	1.49	0.00	6.00
Crew1RdyLnch	0.00	6.00	10.21	0.18	0.71	0.00	3.00
Crew1Ready	3.00	21.00	30.94	1.87	1.45	0.00	3.00
Crew2	4.00	8.00	39.07	0.90	1.00	0.00	4.00
Crew2Rdy	2.00	10.00	57.06	1.65	0.76	0.00	2.00
Crew2Ready	2.00	14.00	30.94	1.25	0.97	0.00	2.00
Crew3	4.00	8.00	39.07	0.90	1.00	0.00	4.00
Crew3Rdy	2.00	10.00	57.06	1.65	0.76	0.00	2.00
Crew3Ready	2.00	14.00	30.94	1.25	0.97	0.00	2.00
Crew4Rdy	2.00	10.00	46.27	1.33	0.94	0.00	2.00
GntcrnRdy	1.00	3.00	0.00	0.00	0.00	0.00	1.00
GntryRdyLock	0.00	2.00	0.00	0.00	0.00	0.00	1.00

Table 7.28 Activities' output

Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur	MinDur	MaxDur	AvInt	SDInt	MinInt	MaxInt
BeamRdyToPick	0.00	2.00	0.00	190.35	20.08	4.04	17.22	22.93	190.35		190.35	190.35
BmMvDwn	0.00	2.00	112.74	281.43	21.51	3.56	19.00	24.02	168.69		168.69	168.69
BmRdyLnch	0.00	2.00	94.08	268.85	9.38	1.10	8.60	10.15	174.77		174.77	174.77
End	0.00	2.00	190.35	346.62	0.00	0.00	0.00	0.00	156.27		156.27	156.27
FinishHangngBm	0.00	2.00	83.80	258.71	10.21	0.10	10.14	10.28	174.91		174.91	174.91
FinishLocking	0.00	2.00	184.06	342.73	5.09	1.70	3.89	6.29	158.67		158.67	158.67
FinishPrpartn	0.00	2.00	73.76	246.59	0.00	0.00	0.00	0.00	172.83		172.83	172.83
FnshPlcGrnd	0.00	2.00	34.72	215.00	4.84	0.28	4.64	5.04	180.28		180.28	180.28
FnshPlcmnt	0.00	2.00	136.76	300.42	31.04	9.39	24.40	37.68	163.66		163.66	163.66
GntCrnStartLnch	0.00	2.00	104.24	277.45	6.24	3.20	3.98	8.50	173.21		173.21	173.21
GntryMveUp	0.00	2.00	136.76	300.42	10.29	0.25	10.12	10.47	163.66		163.66	163.66
GntryPushBck	0.00	2.00	160.60	322.61	21.79	2.37	20.12	23.46	162.02		162.02	162.02
GntryRdyBck	0.00	2.00	147.23	310.54	12.72	0.91	12.07	13.36	163.31		163.31	163.31
LftngUpPrprdBm	0.00	2.00	73.76	246.59	11.08	1.47	10.04	12.11	172.83		172.83	172.83
PlcBmToGround	0.00	2.00	22.93	207.57	9.61	3.08	7.43	11.79	184.64		184.64	184.64
Preparation	0.00	2.00	39.76	219.65	30.47	4.99	26.95	34.00	179.88		179.88	179.88
UnlddTrckLeavs	0.00	2.00	22.93	207.57	10.88	1.36	9.92	11.84	184.64		184.64	184.64
					215.23							

Similar to the interpretation step completed in the previous model (Section7.1.5), the above outputs were interpreted and the logic of the model was found to conform to the concept of the real-world project.

To ensure the validity of the developed model, the study then conducted statusing analysis using the “Animation” capability.

As previously mentioned, animation of the simulation of the current scenario was recorded by the Camtasia® program. For each change that happened in the model (represented by colours changing in the “Animation” view, such as changes in the thickness of symbols for Activities and Queues, etc.), an image was captured and saved. In all, 321 images were recorded for this model, each showing a different process, different states of resources, differences in releasing and feeding resources, etc.

In the following section, 50 states from Part I of the above model have been analysed with the associated discussion presented in Appendix 3.

In the first column, numbers are listed, with each change that occurred in the state of the element given a number, and the numbers representing the sequence of these changes. In the second column, the name of the Combi or Normal Activity is represented using bold font, while a red/blue colour indicates the different states in which elements are held in the system. The next columns are included in Table A2 in Appendix 3 to help in analysing the interactions between the elements, and describe the state of the element as well as the effect of that state on the entire system. The descriptions of the system are coded to represent how many times the system behaviour has changed in accordance with the changes in the elements’ states. For example, state numbers 1–6 led the system to behave on “A” condition with this described in the first row as the description of the system in state 1. In the last column, the figure’s number related to each state is embedded in the table (the related images are presented in Appendix 3).

Using the “Animation” capability helps the modeller (the researcher) to compare the interactions between resources in the model with the logic of the real-world operation. In addition, running the animation helps users to understand the interdependencies between the components. In this way, rather than statusing, users can estimate the required time which each resource should spend in a different status.

7.3.3 "PARAMETERIZING AND RESULTS" OPTIONS

A new model was developed to explore the modelling function of the EZStrobe program, with this model based on the GNRI Strobe Model I (see Section 7.1, Figure 7.2). In this model, a bridge launching operation for "n" number of beams was selected for simulation. The model then needed to be parameterised using the "Parameterizing and Results" modelling element. Moreover, running STROBOSCOPE on this model provided the current study with the opportunity to explore how the parameterised results of the simulation could help with analysing and understanding the behaviour of the operation.

This model was developed and simulated in accordance with the framework presented in Section 7.2 where, firstly, the following assumptions for the model development were formulated:

1- The operation includes the placement of five intermediate beams. The number of instances of Activities in this model is more than 1.
2- The logic of the real-world model including the sequence of Activities, duration for the completion of Activities, content of resources and interdependencies is similar to what was considered in the development of the model in Section 7.1,Figure 7.2.
3- The placement of five beams can be completed continuously. (This assumption was formulated here only to examine the "Parameterizing" capability of EZStrobe. In the real-world project, the operation cannot be processed continuously. Using this assumption also helped with the estimation of the hours required for the delivery of each beam in the project).

As mentioned above, the GNRI Strobe Model I was used as the foundation for model development in this part of the study. As the model should be parameterised for the placement of "n" beams, then the "placement of each beam" is a variation which is dependent on SimTime. By selecting the "Parameterizing and Results" function in EZStrobe, the modeller (the researcher) was directed through a new window called "Shape Data" (see Figure 7.8).

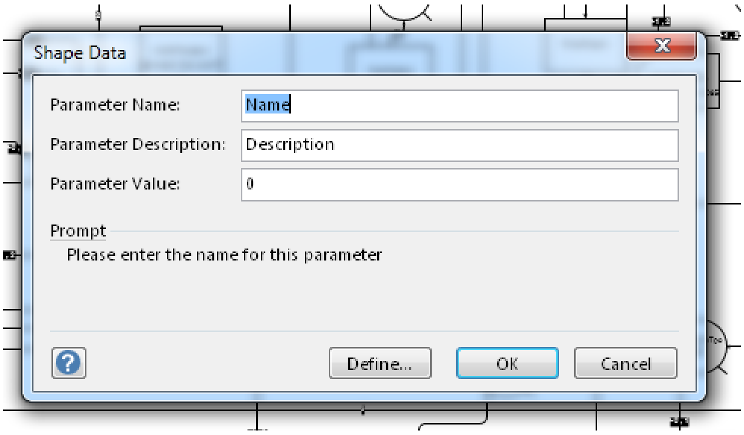


Figure 7.8 "Parameterizing" function in EZStrobe environment

Therefore, at this step, the information presented in Figure 7.9 was entered into the "Shape Data" window.

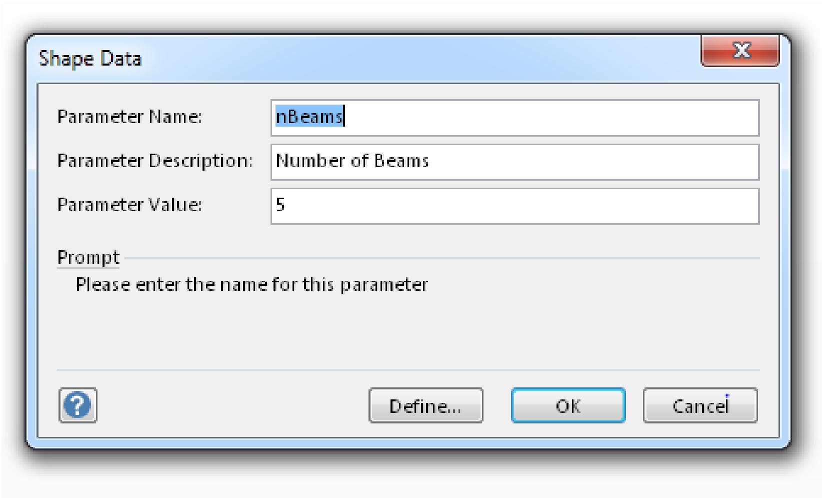


Figure 7.9 Parameter used in simulating GNRI gantry launching operation

As the first span includes five beams, at this step, the number of beams (the "Parameter Value") was considered to be 5.

To formulate the dependency between the operation and SimTime, the formula was entered in the "Results" window, as presented in Figure 7.10.

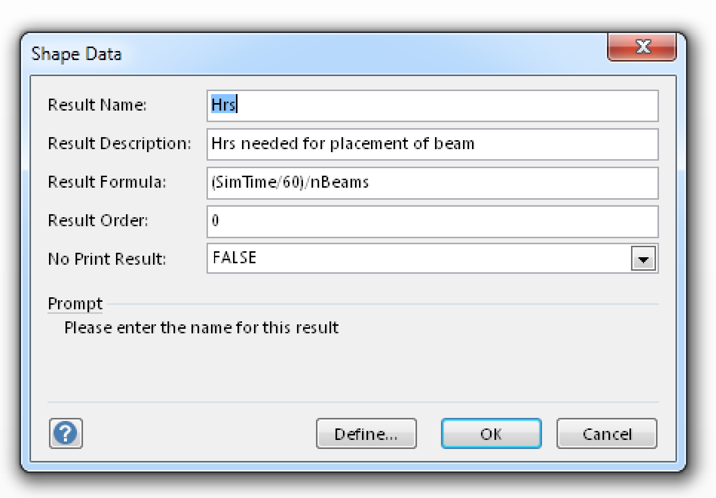


Figure 7.10 Formula for parameterising GNRI gantry launching operation

The model appeared as presented in Figure 7.11 with “Parameterizing and Results” formulations appearing in two new boxes in the top right side of the model window.

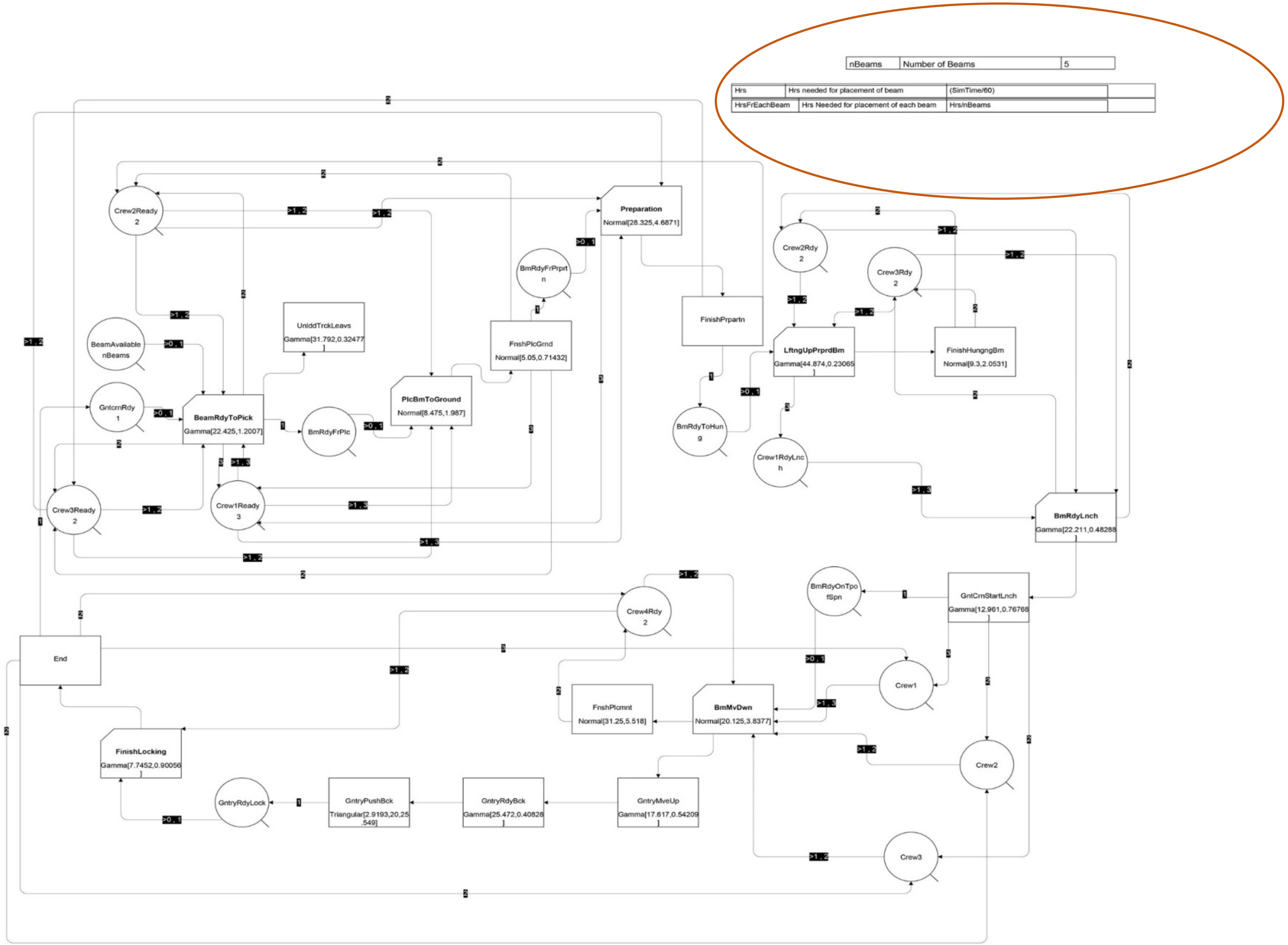


Figure 7.11 Simulated model using “Parameterizing” capability of EZStrobe

The output from running the simulation is summarised in Tables 7.29–7.31.

Table 7.29 Queues' output

Queue	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
BeamAvailable	0.00	5.00	355.85	1.98	1.43	0.00	5.00
BmRdyFrPlc	0.00	5.00	0.00	0.00	0.00	0.00	1.00
BmRdyFrPrprtn	0.00	5.00	0.00	0.00	0.00	0.00	1.00
BmRdyOnTpofSpn	0.00	5.00	0.00	0.00	0.00	0.00	1.00
BmRdyToBHung	0.00	5.00	0.00	0.00	0.00	0.00	1.00
Crew1	15.00	30.00	180.95	6.05	4.29	0.00	15.00
Crew1RdyLnch	0.00	15.00	9.77	0.16	0.68	0.00	3.00
Crew1Ready	3.00	48.00	34.84	1.86	1.46	0.00	3.00
Crew2	10.00	20.00	180.95	4.03	2.86	0.00	10.00
Crew2Rdy	2.00	22.00	67.50	1.66	0.76	0.00	2.00
Crew2Ready	2.00	32.00	34.84	1.24	0.97	0.00	2.00
Crew3	10.00	20.00	180.95	4.03	2.86	0.00	10.00
Crew3Rdy	2.00	22.00	67.50	1.66	0.76	0.00	2.00
Crew3Ready	2.00	32.00	34.84	1.24	0.97	0.00	2.00
Crew4Rdy	2.00	22.00	55.15	1.35	0.94	0.00	2.00
GntcrnRdy	1.00	6.00	0.00	0.00	0.00	0.00	1.00
GntryRdyLock	0.00	5.00	2.16	0.01	0.11	0.00	1.00

Table 7.30 Activities' output

Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur	MinDur	MaxDur	AvInt	SDInt	MinInt	MaxInt
BeamRdyToPick	0.00	5.00	0.00	712.67	25.84	6.65	17.22	32.24	178.17	15.00	156.27	190.35
BmMvDwn	0.00	5.00	112.74	820.45	19.99	3.98	15.06	24.09	176.93	6.60	168.69	183.95
BmRdyLnch	0.00	5.00	94.08	797.94	10.34	2.05	8.12	12.62	175.96	3.03	172.26	178.88
End	0.00	5.00	190.35	897.20	0.00	0.00	0.00	0.00	176.71	13.65	156.27	184.53
FinishHangngBm	0.00	5.00	83.80	788.84	9.77	1.11	8.24	11.10	176.26	2.58	174.16	179.95
FinishLocking	0.00	5.00	184.06	889.81	5.85	1.27	3.89	7.39	176.44	11.87	158.67	183.17
FinishPrpartn	0.00	5.00	73.76	777.13	0.00	0.00	0.00	0.00	175.84	2.48	172.83	178.76
FnshPlcGrnd	0.00	5.00	34.72	742.14	5.15	0.41	4.64	5.76	176.85	2.78	174.36	180.28
FnshPlcmnt	0.00	5.00	136.76	844.54	32.28	8.50	23.73	43.46	176.94	8.92	163.66	182.73
GntCrnStartLnch	0.00	5.00	104.24	810.16	10.35	4.85	3.98	17.32	176.48	3.93	173.21	182.06
GntryMveUp	0.00	5.00	136.76	844.54	10.09	1.30	8.36	11.93	176.94	8.92	163.66	182.73
GntryPushBck	0.00	5.00	160.60	867.69	20.42	3.64	14.26	23.46	176.77	10.32	162.02	186.09
GntryRdyBck	0.00	5.00	147.23	854.14	11.71	1.86	9.51	13.55	176.73	9.06	163.31	182.60
LftngUpPrprdBm	0.00	5.00	73.76	777.13	10.83	1.04	9.75	12.11	175.84	2.48	172.83	178.76
PlcBmToGround	0.00	5.00	22.93	737.03	8.20	2.45	5.11	11.79	178.53	4.75	173.29	184.64
Preparation	0.00	5.00	39.76	747.90	28.75	3.23	25.58	34.00	177.03	2.20	175.12	179.88
UnlddTrckLeavs	0.00	5.00	22.93	737.03	9.72	1.47	7.71	11.84	178.53	4.75	173.29	184.64
					219.29							

Therefore, the sequence of Activities according to the 1stSt results from the simulation is as shown in Table 7.31.

Table 7.31 Sequence of Activities according to simulated model

Sequence	Activity	1stSt
1	BeamRdyToPick	0.00
2	UnlddTrckLeavs	22.93
3	PlcBmToGround	22.93
4	FnshPlcGrnd	34.72
5	Preparation	39.76
6	FinishPrpartn	73.76
7	LftngUpPrprdBm	73.76
8	FinishHangngBm	83.80
9	BmRdyLnch	94.08
10	GntCrnStartLnch	104.24
11	BmMvDwn	112.74
12	FnshPlcmnt	136.76
13	GntryMveUp	136.76
14	GntryRdyBck	147.23
15	GntryPushBck	160.60
16	FinishLocking	184.06
17	End	190.35

In addition to the simulation output, the results based on the entered formula were computed (see Figure 7.12).

```
Stroboscope Simulation System Educational Version
Stroboscope Model Revision of the model 8_4_ 15

** Model input parameters **

Number of Beams: 5


** Calculated results after simulation **

Hrs needed for placement of beam      : 14.9534
Hrs Needed for placement of each beam: 2.99068

Statistics report at simulation time 897.203
```

Figure 7.12 Simulation results for parameters and formula included in model

The results showed that the total hours required for the placement of five beams was almost 15 hours, with each beam needing three hours. In accordance with the assumption, this estimation was only intended to predict the required hours for the placement of intermediate beams. However, the current study, through exploring this capability of EZStrobe, identified how a parameterised model could help in understanding the operation behaviour, and in estimating the required time for the completion of the operation.

7.3.4 "MS EXCEL SPREADSHEET INTERFACE" IN EZSTROBE

Another capability embedded in the design of the EZStrobe program allows users (developers, planners and managers) to access MS Excel graphs of the Queues. The graphs can help with statusing the resources, in turn, enhancing the level of understanding of the system behaviour. This function is accessible through the selection of "Graph population vs time" as shown in Figure 7.13. By selecting and using this option, the MS Excel graphs and EZStrobe output would be produced simultaneously.

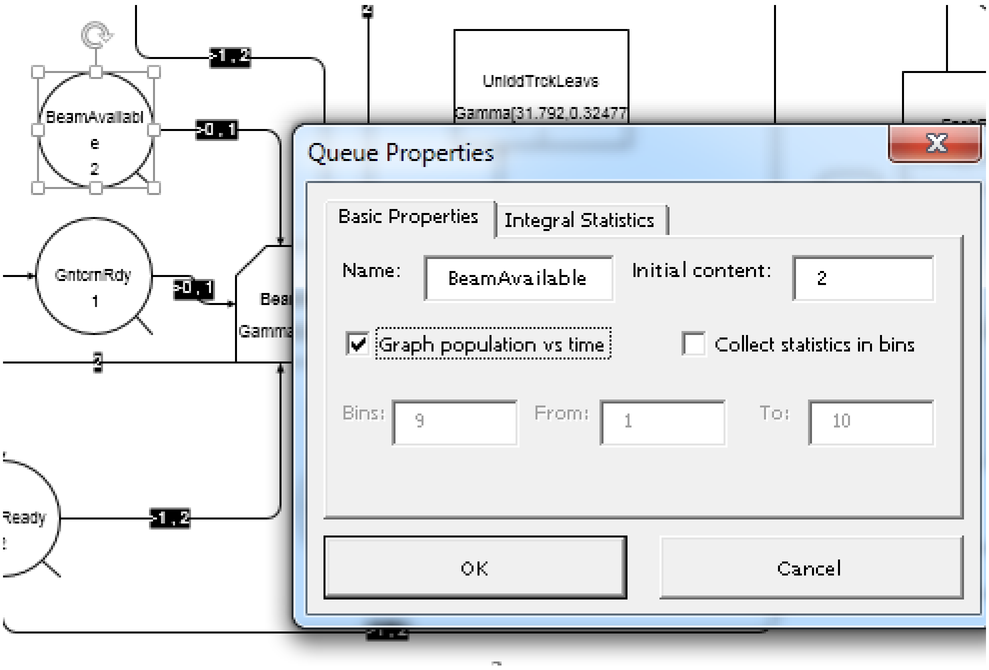


Figure 7.13 MS Excel spreadsheet graph population for Queues

For the running of EZStrobe on the GNRI Strobe Model I, this option was chosen. The resulting graphs on Queues "Crew 1", "Crew 2", "Crew 3" and "Crew 4" are presented in the following paragraphs to illustrate the implications of these MS Excel graphs.

Analysing the states shown in Crew 3's MS Excel graphs illustrates how this crew takes different roles throughout the whole system to accomplish the operations related to Parts I, II and III (see Figure 7.2, GNRI Strobe Model I). The changes of the states of this Queue from Crew3Ready, to Crew3Rdy and, finally, to Crw3 are described below.

Figure 7.14 presents the MS Excel graph result for the "Crew3Ready" Queue. The graph shows the time at which the content of this Queue has been utilised on the completion of a specific Activity in the system. In other words, the graph presents the time at which the Queue holds which role (state) in the system.

As mentioned in Section 7.1, the number of resource units allocated to this Queue is two persons. Crew 3 should be ready at the early step of the operation to allow BeamRdyToPick (Ac.1) to start. In other words, Crew 3's availability is one of the required conditions for the performance of Ac.1.

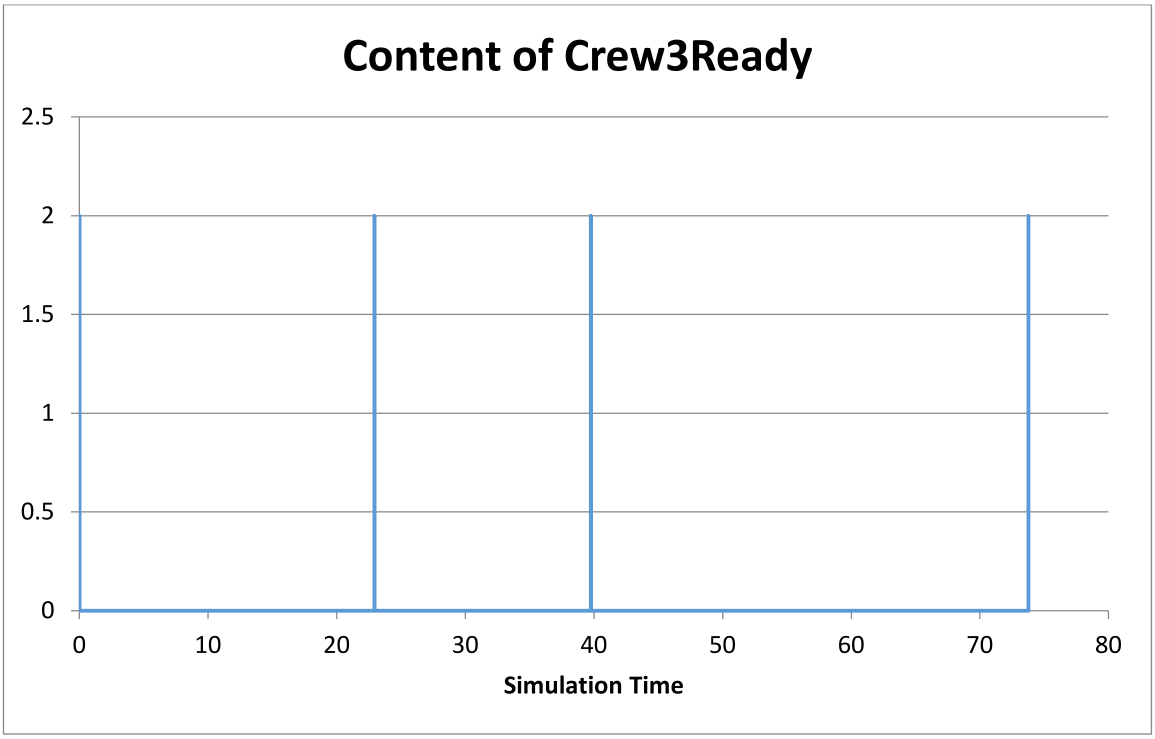


Figure 7.14 Behavioural analysis of Crew3Ready Queue in the system

According to the above MS Excel graph, Crew 3 is available at time 0 in their associated Queue (Crew3Ready); therefore, the Queue feeds its content into Ac.1 at time 0. Then, the crew is busy for about 23 minutes until Ac.1 is completed. At the completion of Ac.1, the crew should be ready immediately for another Activity, the accomplishment of Ac.3. Then, with no hesitation, the content of the Queue (i.e. Crew 3) is fed into Ac.3 (PlcBmToGround). The crew is engaged in the completion of Ac.3 for about 12 minutes. At time 40, when Ac.3 is completed, the Queue receives its content. The content cannot wait in the Queue, as Crew 3 has to be engaged in the completion of Ac.4. Finally, at time 74, Crew 3 finishes its job in this part of the operation. This means that their role in the delivery and preparation finishes once Ac.4 is completed.

To describe the role of Crew 3 in the rest of the operation, the next graph has been analysed. This graph was obtained from EZStrobe in the Queue called Crew3Rdy. The role of the crew changes at time 74 as it has to be ready for the launching operation.

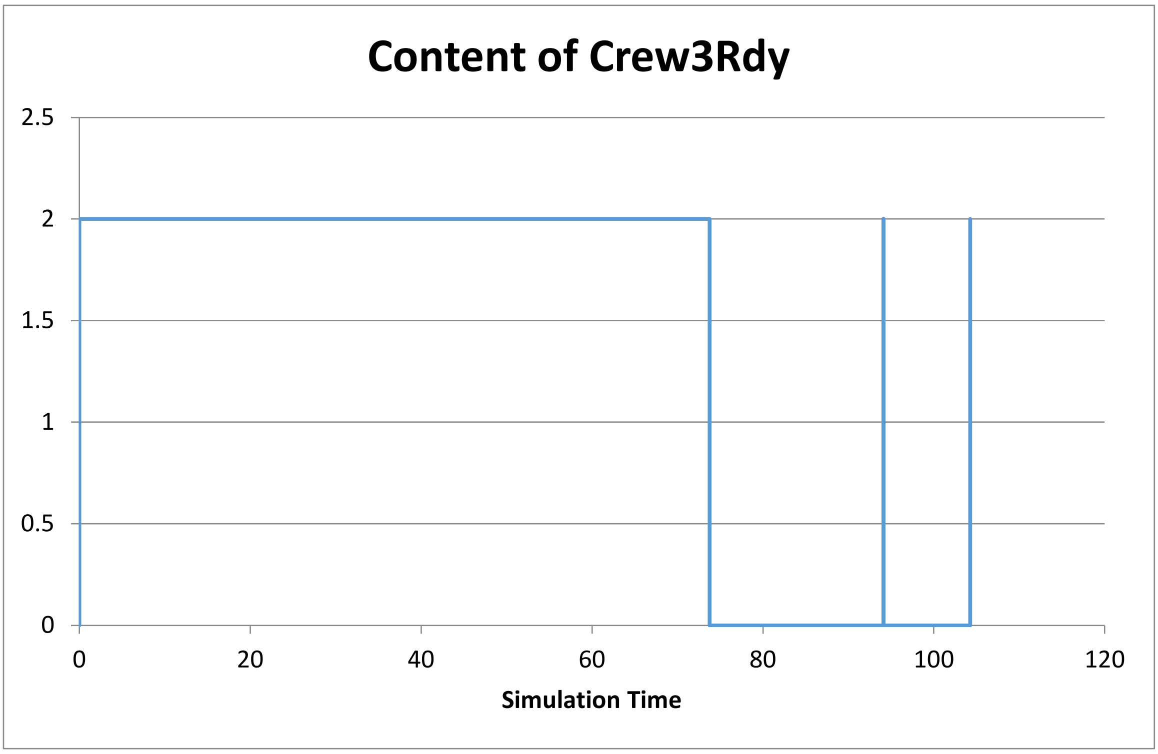


Figure 7.15 Behavioural analysis of Crew3Rdy Queue in the system

As the graph shows, the earliest time that Crew 3 is engaged in the launching operation is at time 74. The crew does not have any idle state between Part 1 and Part 2. When it starts operations on Part 2, the crew is engaged in the completion of two more Activities, Ac.7 and Ac.9. Crew 3 holds this role until time 104, when Ac.9 is completed.

Once again, the crew has to change its role, as Crew 3 should start launching the loaded gantry crane toward the span. The new role is assigned to the Queue called Crew3. The graph for this Queue is presented in Figure 7.16 below.

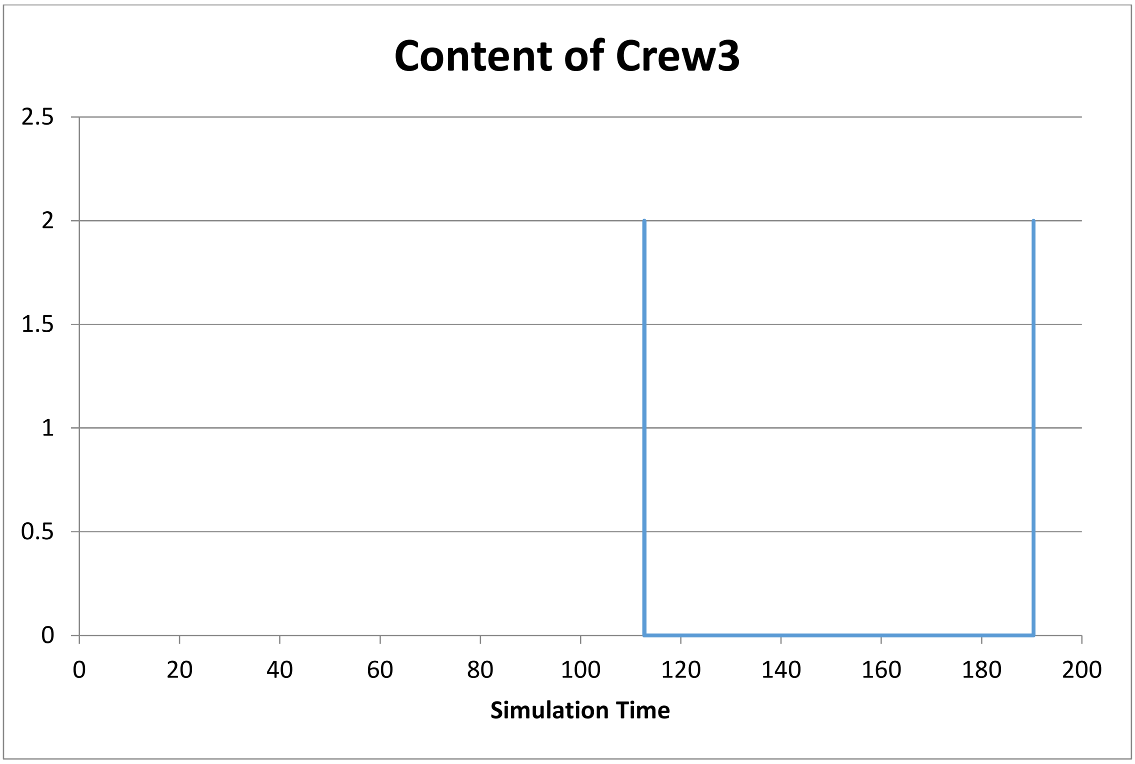


Figure 7.16 Behavioural analysis of Crew3Ready Queue in the system

As the graph shows, Crew 3 is engaged in moving the gantry crane forward from time 113 to time 190.35. Between Part 2 and the last part of the operation, this crew is in the idle state for about 9 minutes. When they engage in the completion of Ac.11 at time 113, they continue non-stop through to the fulfilment of Ac.11, Ac.13, Ac.14, Ac.15 and Ac.16. The statusing results for this crew are summarised in Table 7.31.

Table 7.32 Statusing of Crew 3 in simulated operation

Crew 3				
Queue	**Busy state**	**Activity in progress**	**Idle state**	**Operation part number**
Crew3Ready	0-23	Ac.1		Part 1
	23-40	Ac.3 and Ac.4		
	40-74	Ac.5		
Crew3Rdy	74-84	Ac.7		Part 2
	84-94	Ac.8		
	94-104	Ac.9	104-113	
Crew 3	113-137	Ac.11		Part 3
	137-190.35	Ac.13, Ac.14, Ac.15 and Ac.16		

In the same way, analysis has been conducted of the states of the other resources and is presented in the following sections.

Table 7.33 Statusing of Crew 1 in simulated operation

Crew 1				
Queue	**Busy state**	**Activity in progress**	**Idle state**	**Operation part number**
Crew1Ready	0-23	Ac.1		Part 1
	23-40	Ac.3 and Ac.4		
	40-74	Ac.5		
			74-84	
Crew1RdyLnch	84-104	Ac.8		Part 2
Crew 1			104-113	Part 3
	113-190.35	Ac.13, Ac.14, Ac.15 and Ac.16		

Table 7.34 Statusing of Crew 2 in simulated operation

Crew 2				
Queue	**Busy state**	**Activity in progress**	**Idle state**	**Operation part number**
Crew2Ready	0-23	Ac.1		Part 1
	23-40	Ac.3 and Ac.4		
	40-74	Ac.5		
Crew2Rdy	74-84	Ac.7		Part 2
	84-94	Ac.8		
	94-104	Ac.9	104-113	
Crew 2	113-137	Ac.11		Part 3
	137-190.35	Ac.13, Ac.14, Ac.15 and Ac.16		

Table 7.35 Statusing of Crew 4 in simulated operation

Crew 4				
Queue	**Busy state**	**Activity in progress**	**Idle state**	**Operation part number**
Crew4Rdy	113-161	Ac.11, Ac.12		Part 3
			161-184	
	184-190.35	Ac.16		

As indicated in the above discussion, these results have brought good insight into the system. The graphs can present the availability of the resources and their states over the operation’s cycle time. Moreover, the analysis could be used to manage the time allocated to the engagement/utilisation of resources, as well as increasing the awareness of changes of roles in different time slots.

Throughout Section 7.3, the research study has explored different capabilities of EZStrobe and has addressed how EZStrobe, through its different functions, would facilitate and/or benefit the modeller (the researcher, in this case), the planner team and the manager(s). In this way, the current study could achieve its objectives.

As discussed in Sections 7.1.3 and 7.2, using a larger sample size would help in the enhancement of the validity of the simulated model. Therefore, in the next section, the developed model, GNRI Strobe Model I, is examined with the inclusion of more data sets with these data collected on the construction of Ramp 4. The process, called “Normalizing the model”, has followed the simulation flow chart presented in Section 7.4.

7.4 “NORMALIZING THE MODEL”

The collected data used for the development of the GNRI Strobe Model I (Section 7.1/ Table 7.3) included 40 data sets. Meanwhile, data collection on the construction of Ramp 4 continued, leading to the addition of 54 more data sets to help the study in generalisation of the simulation model and further analysis of the GNRI gantry launching operation.

As discussed in Section 7.1.3, to determine the probability distribution function (PDF), data were analysed using the EasyFit software. Therefore, all of the data collected on Ramp 1 and Ramp 4 were first analysed, with the results of the PDF analysis summarised in Table 7.36 (see also Appendix 4 for the selection of best fit distribution through the EasyFit results).

Table 7.36 Best fit distribution analysis for data collected on Ramp 1 and Ramp 4 construction

Activity number	Activity name	Types of node	Selected best fit distribution	EZStrobe input
Ac.1	BeamRdyToPick	Combi	PERT	PERT [4.3951, 34.74, 38.24]
Ac.2	UnlddTrckLeaves	Normal	Uniform	Uniform [6.2654, 18.387]
Ac.3	PlcbmToGround	Combi	Gamma	Gamma [13.591, 0.62621]
Ac.4	FnshPlcGround	Normal	PERT	PERT [2.8671, 4.4774, 11.543]
Ac.5	Preparation	Combi	PERT	PERT [17.013, 27.008, 48.366]
Ac.7	LftngUpPrprdBm	Combi	Gamma	Gamma [23.956, 0.45192]
Ac.8	FinishHangngBm	Normal	Normal	Normal [9.2935, 2.0783]
Ac.9	BmRdyLnch	Combi	PERT	PERT [3.1736, 9.8075, 17.776]
Ac.11	GntCrnStartLnch	Normal	Gamma	Gamma [13.445, 0.71711]
Ac.10	BmMvDwn	Combi	Normal	Normal [19.511, 5.2967]
Ac.12	FnshPlcmnt	Normal	PERT	PERT [17.192, 30.241, 49.222]
Ac.13	GntryMveUp	Normal	PERT	PERT [4.6364, 7.8146, 26.027]
Ac.14	GntryRdyBck	Normal	Erlang	Erlang [0.48523, 22]
Ac.15	GntryPushBck	Normal	Normal	Normal [20.054, 6.2886]
Ac.16	FinishLocking	Combi	Normal	Normal [8.4239, 2.9435]

The selected best fit distributions were translated into the EZStrobe functions (as presented in the last column of Table 7.36), and entered in the GNRI Strobe Model I. EZStrobe was then run, and the results were tabulated in Table 7.37 and Table 7.38. In this way, the normalised model was obtained and, using the same method as discussed in previous sections, was verified and validated. The current study called this last simulated model “GNRI Strobe Model II”, with this latter model compared to the first model in the Discussion chapter of this thesis to present the level of variability in the construction operation.

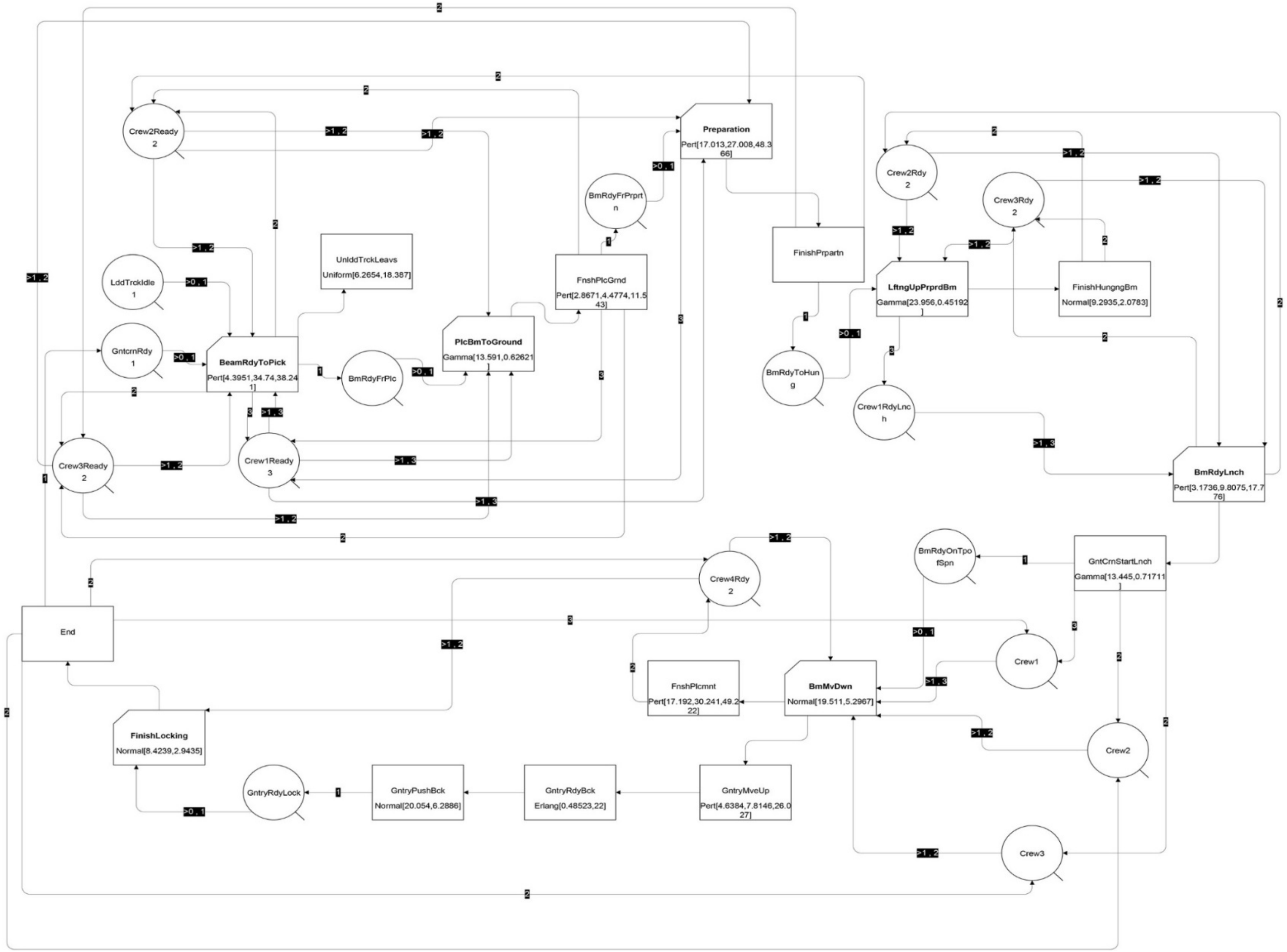


Figure 7.17 GNRI Strobe Model II

Table 7.37 Queues' output

Queue	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
BmRdyFrPlc	0	1	0	0	0	0	1
BmRdyFrPrprtn	0	1	0	0	0	0	1
BmRdyOnTpofSpn	0	1	0	0	0	0	1
BmRdyToBHung	0	1	0	0	0	0	1
Crew1	3	6	0	0	0	0	3
Crew1RdyLnch	0	3	7.05	0.11	0.56	0	3
Crew1Ready	3	12	32.04	1.99	1.42	0	3
Crew2	2	4	0	0	0	0	2
Crew2Rdy	2	6	54.99	1.7	0.71	0	2
Crew2Ready	2	8	32.04	1.32	0.95	0	2
Crew3	2	4	0	0	0	0	2
Crew3Rdy	2	6	54.99	1.7	0.71	0	2
Crew3Ready	2	8	32.04	1.32	0.95	0	2
Crew4Rdy	2	6	45.1	1.4	0.92	0	2
GntcrnRdy	1	2	0	0	0	0	1
GntryRdyLock	0	1	0	0	0	0	1
LddTrckIdle	0	1	0	0	0	0	1

Table 7.38 Activities' output

Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur	MinDur	MaxDur	AvInt	SDInt	MinInt	MaxInt
BeamRdyToPick	0	1	0	0	22.93		23.99	23.99				
BmMvDwn	0	1	101.78	101.78	15.44		15.44	15.44				
BmRdyLnch	0	1	86.65	86.65	7.5		7.5	7.5				
End	0	1	193.65	193.65	0		0	0				
FinishHangngBm	0	1	79.6	79.6	7.05		7.05	7.05				
FinishLocking	0	1	185.49	185.49	8.15		8.15	8.15				
FinishPrpartn	0	1	65.47	65.47	0		0	0				
FnshPlcGrnd	0	1	33.06	33.06	5.39		5.39	5.39				
FnshPlcmnt	0	1	117.22	117.22	34.74		34.74	34.74				
GntCrnStartLnch	0	1	94.16	94.16	7.62		7.62	7.62				
GntryMveUp	0	1	117.22	117.22	6.61		6.61	6.61				
GntryPushBck	0	1	162.68	162.68	22.81		22.81	22.81				
GntryRdyBck	0	1	123.83	123.83	38.85		38.85	38.85				
LftngUpPrprdBm	0	1	65.47	65.47	14.13		14.13	14.13				
PlcBmToGround	0	1	23.99	23.99	9.07		9.07	9.07				
Preparation	0	1	38.45	38.45	27.02		27.02	27.02				
UnlddTrckLeavs	0	1	23.99	22.93	15.32		15.32	15.32				
					242.63							

7.5 SUMMARY

This chapter has presented the analysis and results of data collected from the studied operation (the Great North Road Interchange [GNRI] gantry launching operation) in the case study organisation. Simulation and best fit distribution analysis which were utilised at the analysis step in the current research have been discussed throughout the chapter. To support the study with its formulated objectives, exploration of and experimentation with EZStrobe's capabilities were undertaken, with this including scenario analysis, the "Animation" capability for statusing resources, MS Excel spreadsheet graphical representation of resources vs. time, the probabilistic element function and parameterising the model, all of which were explained in detail.

Furthermore, by interpreting the simulation output in accordance with the logic of the EZStrobe program, the modeller (the researcher) could proceed with comparison analysis between the concept of the simulated model and system behaviour in the real-world project. The relevant results answered this question: "does the simulated model conform to the logic of the real-world fieldwork?" Interpretation and comparison analysis on the different simulated models developed by the current research led the study to formulate some important criteria and identified the simulation steps in a modelling procedure utilising EZStrobe. Moreover, the study was able to build a framework for the implementation of EZStrobe in the bridge launching operation and, accordingly, this helped the current research in covering the knowledge gap in this context. The developed framework was utilised in verifying and confirming the accuracy of the model extensions and scenario analysis.

Two different data sets were used for carrying out the probability distribution function (PDF). The obtained results appear to have addressed the feature of uniqueness within construction operations. The reason is that the best fit distribution function results for the data set collected on the construction of Ramp 1 differ from the results on the data set collected on the construction of Ramps 1 and 4. Through this PDF analysis, the current study has also been able to present the variations in construction operations caused by different constraints to which the operations might be exposed.

Even though the results achieved and presented throughout this chapter have provided interesting and important information for the research objectives, no assertion has been made about the generalisability of the experience of this particular operation to other construction operations. However, the lessons learnt from the knowledge gained in this studied case could benefit the management and planning of construction operations from other perspectives. The next two chapters discuss this further and present the conclusions of the results, as well as the recommendations and contributions to practice.

CHAPTER 8

DISCUSSION OF RESEARCH RESULTS

8.0 INTRODUCTION

This current chapter aims to discuss the results and findings from throughout the exploratory journey presented in Chapters 6 and 7. In these two chapters, the study's significant findings are drawn together to highlight the capabilities of EZStrobe and its applicability in the facilitation of construction operations management.

The main purpose of this chapter is to establish a foundation for synthesising the research findings and, consequently, for delivering the research objectives (see Chapter 9). The two main sections included in this chapter present: (1) the study's main findings as they relate to the understanding of system behaviour and its impact at the scheduling level; and (2) the framework for the implementation of EZStrobe simulation in the modelling of a construction operation.

8.1 FRAMEWORK FOR IMPLEMENTATION OF EZSTROBE AND FORMULATING REQUIRED CRITERIA FOR MODEL DEVELOPMENT

As the use of STROBOSCOPE and EZStrobe is new in the construction management context, their capabilities and implementation have had little recognition. Few examples that explained the simulation procedure using STROBOSCOPE and EZStrobe could be found in the review of the literature. In addition, no framework was available for the implementation of EZStrobe in modelling a construction operation. Moreover, those examples did not cover the particular method of construction for the GNRI gantry launching operation used as the studied case in this research. These reasons plus the uniqueness of this construction operation highlighted the need to conduct a simulation experiment to enable a framework for simulating a construction operation to be developed.

Taking into account the previous recommendations for building a simulation model (see Chapter 4), the current study first identified what the required data were for the simulation of the gantry launching operation. The initial model (whether an ACD [activity cycle diagram] or a simulated model) developed in the preliminary phase of the study also indicated how the verification and validation of the model should be performed. As these initial modelling practices strongly focused on the conformance between the logic of the real-world project and that of the simulated project when the real fieldwork was being undertaken, the study had a good chance to identify how the simulated model could present the operation behaviour as per reality. The modelling procedure needed the addition of some steps, not mentioned in the literature, to enable the modeller (the researcher) to achieve a more accurate model. Those steps are:

1- developing the ACD to enable the simulator's understanding of the system behaviour from different perspectives
2- focusing on the problems of the operation (e.g. deployment of the new method of construction) and its consequences for managerial approaches
3- formulating assumptions according to the concept of the real-world project and the logic of the simulation program, and
4- building the criteria for model verification and validation.

Even though the literature has addressed ACD modelling, the newness of the gantry launching operation method and the absence of a WBS necessitated the development of the particular ACD in the current study. The study needed to develop and verify an ACD model to ensure the developed ACD could present the gantry launching operation behaviour. Following the recommendations from the literature (Section 4.2) for the development of a conceptual model, the criteria for model building as stated by previous scholars were found to have had a strong emphasis on the assessment of their particular model rather than on the assessment of conceptual models. However, the current research undertook the development of the conceptual model in the ACD format (presented in Section 6.5). As illustrated by this experience, the application of different approaches to the analysis of system behaviour could ensure that the simulator was aware of the most suitable way in which to develop and present the activity cycle diagram (ACD).

Moreover, to verify and validate the simulated model, comparison was required between the real-world system and the simulated model. The current study's preliminary phase found that the interpretation of the simulation's outputs played an important role in the completion of this comparison. On the other hand, the simulation's outputs varied depending on the variations and parameters included in the simulation model. Therefore, some assumptions needed to be formulated describing the parameters, equations, numbers of entities, etc. with these entered in the simulation as input, as well as the formulation of assumptions regarding the expected output according to those variations. The basic criteria formulated through this approach would enable the simulator (the researcher) to see whether or not the simulated model worked as per the assumptions.

Consequently, the criteria for the model verification and validation (Section 7.2) were determined after the main phase of the study was completed. Those criteria were:

1- Total duration should be equal to the life cycle of the real-world project.
2- The number of resources should match the content of resources in the real-world project.
3- The simulation should finish due to "Lack of Resources".
4- The sequences of activities and interactions between activities and resources should conform to the concept of the real-world project.

Furthermore, the developed framework, in addressing the normalisation of the simulated model, has added one of the new steps to the simulation procedures, as recommended by previous studies. This was possible as the EZStrobe program has the capability of considering best fit analysis results for the simulation of an operation, with increasing the sample size then found to be supportive for testing a simulated model ("Normalizing" the model, see Section 7.4). This step could ensure that the modeller knows how much the simulated model would be applicable in another similar operation. Different results were obtained for the best fit analysis of two data sets collected on the construction of Ramps 1 and 4. The differences obviously reflect the different system behaviour for the construction of these two ramps. While the behaviour differs from one ramp to the other, the simulated models using those different data sets could still meet the model building criteria formulated in Section 7.2. In this way, the study's findings could add another key step to the simulation of an operation, that of normalising the simulated model, with the purpose of enhancing the reliability of the developed model.

8.2 ADVANTAGES OF SIMULATING AN OPERATION AT THE LEVEL OF SCHEDULING

1- Dealing with the new method of construction using the gantry launching operation (for the GNRI), as presented in Section 6.1, makes the planning and management of the operation more cumbersome. The absence of the WBS for the gantry launching operation meant that the master plan could not be developed in detail at the beginning of the project. The level of detail of the scheduling started to improve during the time the researcher was taking field notes on the preliminary phase of the study. Furthermore, by delving into the behavioural analysis of the operation and preparing the data for the simulation experiments, attention was drawn to the constraints and details of the operation which could have a significant impact on the execution of the gantry launching operation (for the GNRI). Simulating the gantry launching operation could bring good insight into the system behaviour through determining which variations might influence the operation's cycle time. Indeed, through simulating the different scenarios utilising the capabilities of EZStrobe, as presented in Section 7.3, the study was able to build a list of these variations. The list includes the number of specific resources/equipment required for the gantry launching operation, such as auxiliary supports, runways and winches, thus leading to progress through additional steps rather than through the regular steps (see the simulated model presented in Appendix 5). With the organisation given the method of construction for the beam launching operation for the first span, it was not feasible to consider the initial master plan for use in addressing the impact of the limited number of these resources and equipment on the beam launching operation for future spans.

In addition, with the master plan developed based on daily work progress, it could not present the hourly details of the operation's progress. However, simulating these changes as a new scenario indicated how many hours were required for the completion of additional work, such as shifting the auxiliary support (Appendix 5)

2- The progress of the operation faced different challenges due to the shape and type of beams (intermediate and edge). Therefore, the scenarios simulated in subsections 7.3.1.1 and 7.3.1.2 could help with understanding the difference in the operational hours needed for the placement of edge beams and intermediate beams.

In summary, all perceptions gained by the study through the collection and analysis of data for simulating the case project and all of the study's results from the simulated models were regularly reported to and discussed with the case study team (the manager and planning team). The project team responsible for the gantry launching operation (for the GNRI) reflected the perceptions gained in the master plan, the LPS's weekly plan and the look-ahead plan. Moreover, with the development of a more reliable plan, the project was completed a few weeks before the estimated date (see Appendix 6 for further details).

8.3 ADVANTAGES OF SIMULATING AN OPERATION FOR UNDERSTANDING FEATURES OF CONSTRUCTION OPERATIONS

Collecting data on the construction of Ramp 1, with analysis of the behaviour using best fit distribution, built a good insight into the uniqueness and the complex behaviour of the gantry launching operation. The same method of construction was applied for the construction of Ramps 1 and 4; however, the collection of different data sets and the analysis results indicated the differences in operation behaviour over the period during which these two ramps were being constructed (see probability distribution function [PDF] results in Appendix 4). Probability distribution function (PDF) analysis not only indicated that construction operations were unique and complicated but also helped the study to identify factors which caused the operations to behave in a unique way, despite the same method of construction being applied. The identified factors were as follows: weather conditions, seasons, traffic closure management, limited number of plant/equipment and structural specifications.

8.4 SUMMARY

This chapter has presented the overall findings of the research (see Chapters 6 and 7). The learning from the simulation experiments was completed in Chapter 6, with Chapter 7 bringing this together to present how EZStrobe can be utilised, and how its utilisation could benefit construction managers and planners.

As illustrated by the current research, through the experience of simulating a construction operation, EZStrobe has been shown to be capable of facilitating the management of operations by providing operations managers and planners with good insight into system behaviour. Furthermore, the study's developed framework for simulating a construction operation using EZStrobe could facilitate the deployment of this new simulation program as well as enhancing the level of accuracy of the simulated model.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.0 INTRODUCTION

This chapter outlines the original contributions made by the current research to productivity management in the New Zealand construction industry. These contributions are presented through synthesising the research findings, with the synthesis presented so that it answers the research questions and delivers the objectives of the research (see Chapter 1).

This chapter starts with this introduction and then the overview of the research (Section 9.1), with this followed by four main sections in accordance with the main objectives of the study. These discussions are followed by a set of recommendations from the current research and, finally, the chapter provides concluding remarks and suggests possible future research opportunities that would extend the current research.

9.1 OVERVIEW OF THE RESEARCH

This research study intended to explore not only which simulation-based technique could improve the productivity of construction operations, but also how this technique could be utilised to achieve this outcome. The research study commenced by finding and selecting the most recent simulation-based techniques. Exploration then continued to find a construction project (or projects) which could provide opportunities for the implementation of the selected simulation technique (EZStrobe).

Due to the impact of the study's limitations on case study project selection (see Section 5.8.1), the only opportunity available was to select a single case project (described in Sections 5.3.3 and 6.1). The study then developed an analytical research framework, as presented in Chapter 5, Figure 5.3, with this framework designed to support the study in achieving its objectives through the single case project.

In accordance with the research methodology framework and the analysis approaches (presented in Chapter 5, Section 5.9), the study began by gathering information, whether through participant observation, field note taking or documentation from the selected case project, which provided input for the specifically developed database. The collected information included the duration of the operation tasks (activities); resources; interactions between resources; work progress instructions (work breakdown structure

[WBS]); and constraints and requisites for performance tracking according to the organisation's practice of using the Last Planner System (LPS).

The data collected from the different sources of evidence available in the case study were utilised for the two phases of model development (an ACD as a conceptual model and a simulated model of operation). In the first phase, preliminary data collection and analysis were completed using data gathered from the construction of the first span (Span 7) in Ramp 1 (see Chapter 6). The placement of the first beam in Span 7 was mostly investigated to see how the method of construction provided by the gantry machine supplier would be applicable in the real-world project. At the same time, the study pursued and performed the development of the database, followed up the Last Planner (LP) meetings, and undertook analysis of the literature review and the extant documents. Thus, the study obtained the initial WBS, the ACD and the initial simulated model (see Section 6.5). The results from those achievements built a foundation for the main phase of data collection, as presented in Chapter 7. As the system/operation behaviour became clear, the study developed a list of required information, with this, in turn, supporting the study in constructing its validity.

Maintaining the chain of evidence and improving the organisation database continued within the main phase of the study (Chapter 7). The database development was finalised at the time when Span 2 of Ramp 1 was undergoing construction. Three different versions of the database and the constant recording of information brought the study to the enhancement of the reliability of the required data for simulating the gantry launching operation (see Section 5.4).

In addition, field note taking based on site visits continued, thus leading to gaining deeper insight into the system behaviour. The constraints and some reasons that changed the operation procedure were identified with these taken into account for later simulation experiments. Exploring the capabilities of EZStrobe simulation provided a good chance of analysing the interactions between resources and of statusing the resources over the period of the progress of the operation.

In the following four sections, the research findings presented in Chapters 6, 7 and 8 are synthesised to support the current study in the delivery of its research objectives, as reported in Chapter 1.

9.2 SIMULATION AS A SUITABLE NEW PLANNING TOOL FOR THE MANAGEMENT OF CONSTRUCTION OPERATIONS

The review of the literature (Chapter 3, Section 3.1) on construction planning techniques revealed that traditional planning techniques, which are designed on the basis of the critical path method (CPM) concept and other time-based methods, cannot account for unexpected site conditions, repetitiveness and the complex features of construction operations.

As Russell and Dubey (1995) proposed, traditional planning techniques could work well when the required resources for the completion of activities are available at the right time. Furthermore, April et al. (2004) added that mathematical equations cannot be adopted for construction operations planning due to the high level of complexity of these operations. In an attempt to support construction planners/managers, recent studies have provided them with computer-based approaches called “simulation”.

As proposed by Srisuwanrat (2009), these technologically-based approaches are developed with the main purpose of improving project scheduling and accelerating the decision-making process, while capturing the complicated interactions between the construction project’s components, feedback loops and the repetitive behaviour of its operations. Furthermore, the review of the literature on the implementation of simulation in construction showed that, although simulation has been successfully applied, construction organisations are not yet keen to deploy these approaches in construction operations, as the majority of simulations need IT knowledge and programming skills.

To overcome these difficulties, a simulation technique which uses MS Visio for model building has been developed using a three-phase activity scanning (AS) strategy, and utilising STROBOSCOPE as a process-level engine. This recently developed simulation program is called EZStrobe (see Section 3.1.1 and subsections 3.1.2.3 and 3.1.2.4). The advantages of STROBOSCOPE have been proven by scholars such as Cor and Martinez (1999), Martinez (1996), Fulenwider (2002), Zaheer (2000) and Fu (2013). In addition, EZStrobe has been claimed to be a powerful graphical tool that users (modellers, managers and planners) with limited simulation experience can easily implement in their projects. The literature has shown that, although EZStrobe has already been tried in a few projects, such as tunnelling and asphalt paving operations, its implementation has not yet become widespread. The reasons could be the newness of EZStrobe, the absence of a sound framework for its implementation, or that it has not been extended to commercial packages.

Through the review of the literature, the current study identified this simulation-based technique as a suitable planning tool to support managers and planners with decision making as well as enhancing the reliability of their operations planning. Among construction simulation tools, EZStrobe has been selected as the technique with the most potential to provide an exploratory opportunity for the current research in the construction context where there is less recognition of its implementation.

9.3 SELECTING THE POTENTIAL CASE PROJECT

As illustrated in the review of the literature, the utilisation of EZStrobe had been limited to a few construction projects, such as asphalt paving and tunnelling operations. However, the current study aimed to identify new construction operations which could provide the opportunity to extend the implementation of EZStrobe in the construction industry. In searching for potential case projects in New Zealand, a bridge construction project which utilised a new construction method called the “gantry launching operation” was found to be a good case for this exploratory research study. Other reasons that motivated the current study to choose this project were as follows:

1- the project’s schedule generally matched the timetable of the current research;
2- utilisation of a new method of construction in the project could make the management and planning more complicated due to the absence of a work breakdown structure (WBS) for the bridge launching operations in which a new machine, the gantry crane, was being deployed; and
3- in line with the Building a Better New Zealand (BBNZ, 2011) report, the selected case project was seeking an improvement in its productivity rate.

As the research aimed to not only explore the capabilities of EZStrobe but also to develop a framework for simulating the selected operation (Chapters 6 and 7), the selected case was found to be supportive for carrying out this research study from a variety of aspects.

9.4 SIMULATING THE CASE PROJECT

As previously stated, the current research selected EZStrobe simulation to model a bridge construction project where a new method of construction called the “gantry launching operation” (for the GNRI) was utilised. However, the absence of a WBS for the gantry launching operation, plus the newness of EZStrobe in the construction industry, brought the opportunity to explore two of the objectives formulated by the current study (Objectives 2 and 3, as presented in Section 1.2.2).

Site visits, field note taking and document analysis were firstly employed to understand the operation behaviour. The major focus was on the sequence of activities, resources utilisation and interactions between resources. To present the work progress, the study then developed a conceptual model using traffic light symbols and the ACD on the completion of Span 7 on Ramp 1. That conceptual model was then revised a few times to enable the modeller (the researcher) to develop a final version (in the ACD format) which fitted the logic of the EZStrobe program (Figure 6.16).

The preliminary ACD model built a foundation for the first attempt to simulate the operation. At that stage, the simulation experiment was completed through the procedure recommended in previous studies. The study could therefore list the data required for modelling and transfer these data into the required format to be fed into the EZStrobe program in the preliminary phase. Simulating the initial model developed based on the construction of Span 7 (Figure 6.18) showed how the concept of the simulated operation would conform to the concept of the real-world operation. The study then identified the simulation output that needed to be interpreted to compare the model concept with the logic of the real-world operation. The output comprised parameters related to: Tot (total number of items started in activities); 1stSt (time at which first instance started); LstSt (time at which last instance started); and AvDur (average duration of activities).

At the end of the preliminary phase, the study found that the initial model should be revised due to the reasons listed below:

1- Non-computed parameters for 1stSt and LstSt, for example, BmLnchToSpn7 in Table 6.15.
2- Incorrect results for 1stSt and LstSt: the model includes some activities which only have one instance; therefore, according to the logic of EZStrobe, 1stSt should have a result equal to that of LstSt. However, for some activities, such as UnlddCrnLock and UnlddCrnStpSpn7 presented in Table 6.15, the computed 1stSt differs from the computed LstSt.
3- AvDur computed for some activities did not match their life cycle in the real-word operation.

However, through the revision phase, the study could resolve these issues and finally develop an initial framework for the implementation of EZStrobe (see Figure 6.22). To achieve the study's Objectives 2 and 3, the exploratory research continued through the main phase in which the rest of Ramp 1 and the whole of Ramp 4 were constructed. The final version of the WBS in the ACD format plus the EZStrobe modelling framework were finally delivered as part of these objectives. Consequently, the developed framework illustrated the additional steps that needed to be added to the procedure for simulating an operation using EZStrobe (see Sections 7.1 and 7.2).

Moreover, the simulation experiments completed and reported in Chapters 6 and 7 brought a new insight to the behaviour of the gantry launching operation (for the GNRI) through introducing best fit analysis (or the probability distribution function [PDF]) utilising the EasyFit program. Calculating the best fit distribution functions supported the current study in delivering its objectives and proved how complex and unique the construction operation was due to the variations arising from constraints in the real-world operation. With the best fit distribution results for Ramp 1 differing from the results obtained for Ramp 4, the study identified some reasons, such as weather conditions, seasons, traffic closure management, limited number of plant/equipment and structural specifications, that could contribute to changes in the process behaviour between the construction of these two ramps.

9.5 APPLICABILITY OF SIMULATION IN CONSTRUCTION MANAGEMENT

Objective 4 of the current study, as introduced in Section 1.2.2, was delivered through exploring the capabilities of EZStrobe (see Section 7.3). Four major functions in EZStrobe: "Probabilistic Branch"; "Animation Capability"; "Parameterizing and Results"; and "MS Excel Spreadsheet Interface" were examined by modelling different scenarios and analysing the system behaviour (statusing the resources). The implementation framework for EZStrobe that was developed in line with the first three objectives of the current study was utilised to:

1- Simulate the scenario of the launching and placement of the edge beam (Section 7.3.1)
2- Simulate the side shifting in the beam placement when the edge beam was placed (Section 7.3.1)

3- Analyse the resource interactions and the understanding of system behaviour (Sections 7.3.2 and 7.3.4)
4- Parameterise and normalise the model (Sections 7.3.3 and 7.4).

Through findings from this work, the study illustrated the extent to which EZStrobe could be utilised and how the deployment of EZStrobe could benefit the management and planning of construction operations. As presented in Section 8.2, having a better understanding of the gantry launching operation could facilitate the scheduling of the project. When the managers and planners gained better insight into the system behaviour, the schedule could be developed in a more reliable way, taking into account the constraints to which the gantry launching operation may be exposed in the real-world operation.

9.6 CONTRIBUTIONS OF THE RESEARCH

The study has contributed to productivity management, the decision-making process, and the management and planning of construction operations through the support of technologically-based approaches, in this case, simulation. The following summary lists the specific contributions made by this study to the body of knowledge:

1- The study has provided useful information on simulation-based techniques and their advantages in construction operations management, focusing on New Zealand's construction sector. The study selected the most recent simulation program, EZStrobe, which is claimed to be user-friendly and has been successful in different perspectives. Through the review of the literature, the study identified that the selected simulation program had not yet been utilised in a wide range of construction operations. As few EZStrobe experiments had presented the modelling procedure in the literature, the current study deployed EZStrobe for the first time in one of the largest construction operations in New Zealand. Consequently, the framework for the implementation of EZStrobe was developed, embedding new steps in addition to what had been proposed by previous studies. These new steps comprised the following: conceptual model development; translating or transferring the model concept into the ACD format; formulating the assumptions; more details on the best fit analysis (using the EasyFit program); verification and validation of the model through comparing the model concept with the logic of the real-world operation; and assessing the model in accordance with the four main criteria.

2- The study has advanced the understanding of the features of construction operations. The features of complexity and uniqueness were presented through probability distribution function (PDF) analysis. Moreover, the study identified the factors which caused the operation to behave in a unique and complicated manner. The factors presented in the list of constraints included weather conditions, seasons, traffic closure management, limited number of plant/equipment and structural specifications.

3- The study also found a significant link between the understanding of operations and operations management. The worst-case scenario could be when a new method of construction is utilised. However, in the case of deploying the gantry launching operation in the New Zealand case project (the GNRI), both an understanding of the gantry launching operation and the development of a WBS were identified as necessary prior to simulating the operation. (This point was highlighted even more through improving the Last Planner System (LPS) implementation in the case project. [See Appendix 6.])

4- No experience of EZStrobe utilisation in the New Zealand construction sector was available to present the conditions in which such a simulation could be utilised and the extent to which simulation could support the New Zealand construction industry, thus identifying the major concern relating to productivity improvement. However, the study has gone further by presenting the capabilities of EZStrobe through analysing system behaviour (focusing on resource interactions and the statusing of resources) and scenario analysis. In this way, the study can present EZStrobe as a capable decision-making support (DMS) tool which could facilitate the management and planning of construction operations. (This point was highlighted even more when the Last Planner System (LPS) implementation in the case project was successful in developing a more reliable plan and in controlling the occurrences of the constraints. [See Appendix 6.])

5- The study found the lack of an appropriate database for collecting data on construction operations as one of the barriers to the utilisation of simulation. Model development requires reliable data which can be translated into a simulation language (in this case, EZStrobe language in the format of the ACD) to present the logic of a real-world operation. Therefore, the current study developed a spreadsheet template to help with recording data and for later retrieval of information when it was required (see Section 5.4). In this way, the need for database development was introduced as a key foundation for the simulation process.

9.7 RECOMMENDATIONS

The recommendations arising from the current research study are presented, firstly, as recommendations to the New Zealand construction industry and, secondly, as recommendations for future research work.

9.7.1 RECOMMENDATIONS TO THE NEW ZEALAND CONSTRUCTION INDUSTRY

To project managers, construction operations managers and planners

The following recommendations are to assist project managers, construction operations managers and planners to enhance the productivity rate of their operations and to facilitate their managerial approaches:

1- Deployment of simplified versions of simulation-based approaches, such as EZStrobe, in the management and planning of construction operations: this will enhance their insight into system behaviour. This is especially the case when managers and planners have to deal with new construction methods in their project. The better the understanding of the operations, the more reliable the plan and the higher the level of detail that can be achieved. In addition, by simulating different scenarios, managers and planners would be able to see the consequences of different decisions before applying their decisions in real-world operations.

2- Integrating advanced technology to improve construction data warehousing: this would create the opportunity to review system behaviour over different time periods and to learn from past experiences. In addition, an appropriate database would provide the project team with a good opportunity to share experiences with other construction projects in line with “lean” management principles. Proper data recording and utilisation would also help with improving and/or facilitating the implementation of “lean” principles and the Last Planner System (LPS) as this would provide LPS users with more reliable data. Consequently, the level of collaboration facilitated by the use of the LPS in productivity management would be improved.

9.7.2 RECOMMENDATIONS FOR FUTURE RESEARCH STUDIES

The current study recommends further research studies in the following areas that could expand on its findings:

1- The study explored the capabilities of EZStrobe in modelling a construction operation through simulating a particular construction operation that comprised the gantry launching method. Moreover, the simulation experiments completed throughout the current research led the study to develop the framework for the implementation of EZStrobe. Therefore, further studies are required to extend the current research findings by utilising the developed modelling procedure framework in simulating other construction operations to help with generalising the framework.

2- The study addressed the uniqueness and complexity of construction operations through the simulation models developed for the gantry launching operation. The study presented the best fit analysis (PDF analysis) that not only helps with simulating an operation but also assists with understanding the operation behaviour and, consequently, identifies the causes of behavioural changes in the desired system. Future research could be carried out in the context of the behavioural analysis of construction operations using PDF analysis.

3- The study has provided a basic understanding of one of the key requirements for the deployment of EZStrobe, namely, the development of an appropriate database which would enable construction project teams to record and utilise data in a more reliable manner. Further studies on this aspect would help to develop a simulation database so construction project teams could record related information, thus enabling the planning and management teams to retrieve this information any time it was required. Moreover, the simulation database could be easily utilised for simulating different scenarios and, consequently, for deciding on any changes required in accordance with the simulation output.

4- Further studies on the need for the development of a construction database, as well as the need for integrating IT in construction management, could also present how these technologically-based ideas could facilitate and improve managerial approaches, such as “lean” management and its tool, the Last Planner System (LPS).

5- The study showed how a simplified simulation-based technique, such as EZStrobe, can be employed in modelling an operation with no need for knowledge of IT or programming skills. Future studies could extend beyond experiments by focusing on endorsement of the implementation of these simulations, training those in construction workstreams in different positions (e.g. site supervisors, managers, planners, etc.) to investigate how and to what extent the simulation could be taught and utilised.

9.8 CONCLUDING STATEMENTS

The current research has explored the potential for the deployment of a simulation-based technique in operations management and planning by focusing on productivity improvement in the New Zealand construction industry.

The study belongs to the interpretivist paradigm. It has been completed on the basis of a single embedded case design in which document analysis and participant observations were the main methodologies for data collection. The principles employed for the case study data collection comprised using multiple sources of evidence, creating a case study database and maintaining a chain of evidence. To analyse the data, the current study utilised PDF analysis (best fit analysis) using the EasyFit program, and scenario and animation analyses using the EZStrobe simulation program. The study found that EZStrobe possessed features which enabled it to be easily implemented in modelling a complex project as it does not require IT knowledge and programming skills. Furthermore, with the particular functions included in the EZStrobe program (e.g. parameterising as well as animation capabilities), the program becomes highly capable in scenario analysis and, consequently, in supporting the decision-making process.

In the current study, the EZStrobe program was employed for the first time in one of the largest construction projects in New Zealand, with this project utilising a new method of construction for bridge operations. The new construction method called the “bridge launching operation” had not been modelled by EZStrobe prior to the beginning of the current study. However, the study has had a good opportunity to explore the capabilities of the application of EZStrobe through modelling a new construction operation. A framework for the implementation of EZStrobe for modelling the gantry launching operation was then developed by this research. The developed framework illustrated the steps that needed to be completed to enable the modeller (in this study, the researcher, but, otherwise, the modeller could be anyone from the operations team) to achieve a more accurate model. The study also found that some steps included in the developed framework have not been mentioned or fully explained by previous researchers.

In addition, the requirements for model building using EZStrobe have been identified, with the development of the database introduced as a key foundation for model development. The recording and utilisation of the project's data were not only being used for simulating the operation, but the data could also help with analysing the behaviour of the operation. As a result, the study could address the factors which make construction operations behave in ways that are complex and unique. This understanding not only supported the current study, but could also assist other researchers with their calls for technologically-based techniques to be utilised. Furthermore, behavioural analysis conducted by the study could provide project managers, construction operations managers and planning teams with good insight, eventually assisting them with the development of a high-level and more reliable schedule. As the case project was applying "lean" principles by using the Last Planner System (LPS), an improved and greater understanding of the system behaviour could help with facilitating the LPS implementation. Rather than the factors mentioned above contributing to the complexity of the operation, enhancing the level of the LPS implementation could lead to the the project identifying more variations that could cause the operation to fail to meet on-time delivery (see Appendix 6).

To conclude, it is hoped that this thesis has contributed to the existing body of knowledge and practice by enhancing the application of simulation and decision-making support (DMS) tools. Ultimately, this will support project managers, construction managers and planners to improve managerial approaches as well as project delivery.

REFERENCES

Abbasian-Hosseini, S. A., Nikakhtar, A., & Ghoddousi, P. (2014). Verification of lean construction benefits through simulation modeling: A case study of bricklaying process. *KSCE [Korean Society of Civil Engineers] Journal of Civil Engineering, 18*(5), 1248-1260.

Abduh, M., & Ginting, A. (2003). Selection of the Pasupati Bridge's construction method using simulation. *Proceedings of the 9th East Asia-Pacific Conference on Structural Engineering and Construction (EASEC),* Bali, Indonesia, December.

Abduh, M., Pratama, A., & Iskandar, N. (2010). Resources optimization of the earthmoving operation using simulation. *Symposium of the 5th Civil Engineering Conference in the Asian Region and Australasian Structural Engineering Conference.*

Abduh, M., Shanti, F., & Pratama, A. (2010). Simulation of construction operation: Search for a practical and effective simulation system for construction practitioners. *Proceedings of the Symposium of the First Makassar International Conference on Civil Engineering (MICCE).*

AbouRizk, S. (2010). Role of simulation in construction engineering and management. *Journal of Construction Engineering and Management, 136*(10), 1140-1153. doi: 10.1061/(ASCE)CO.1943-7862.0000220

AbouRizk, S., & Hague, S. (2009). An overview of the COSYE environment for construction simulation. *Proceedings of the Symposium of the Winter Simulation Conference*, Institute of Electrical and Electronics Engineers (IEEE), Piscataway, NJ.

AbouRizk, S., Halpin, D., Mohamed, Y., & Hermann, U. (2011). Research in modeling and simulation for improving construction engineering operations. *Journal of Construction Engineering and Management, 137*(10), 843-852. doi: 10.1061/(ASCE)CO.1943-7862.0000288

AbouRizk, S. M., Halpin, D., & Wilson, J. R. (1994). Fitting beta distributions based on sample data. *Journal of Construction Engineering and Management, 120*(2), 288-305.

Agranoff, R., & Radin, B. A. (1991). The comparative case study approach in public administration. *Research in Public Administration, 1*, 203-231.

Ahuja, H. N., & Nandakumar, V. (1985). Simulation model to forecast project completion time. *Journal of Construction Engineering and Management, 111*(4), 325-342.

Ailland, K., Bargstädt, H.-J., & Hollermann, S. (2010). Construction process simulation in bridge building based on significant day-to-day data. *Proceedings of the Symposium of the Winter Simulation Conference.*

Allison, G. T. & Zelikow, P. (1999). E*ssence of decision: Explaining the Cuban missile crisis*, 2nd edn. Longman.

Alvanchi, A. (2011). *Incorporating the effects of complex dynamic interactions in the construction decision making process*. ProQuest, UMI Dissertations Publishing.

Alves, T. D. C., Tommelein, I. D., & Ballard, G. (2006). Simulation as a tool for production system design in construction. Chapter 1 in *Proceedings of 14th Annual Conference of the International Group for Lean Construction*, Santiago, Chile. http://iglc.net/Papers/Details/404

Alzraiee, H., Zayed, T., & Moselhi, O. (2015). Dynamic planning of construction activities using hybrid simulation. *Automation in Construction,* 30th ISARC

Special Issue, *49*, Part B(0), 176-192. http://www.sciencedirect.com/science/article/pii/S0926580514001903

Amaratunga, D., Baldry, D., Sarshar, M., & Newton, R. (2002). Quantitative and qualitative research in the built environment: Application of “mixed” research approach. *Work Study, 51*(1), 17-31.

April, J., Better, M., Glover, F., & Kelly, J. (2004). New advances and applications for marrying simulation and optimization. *Proceedings of the Symposium of the 36th Winter Simulation Conference.*

Arbez, G., & Birta, L. G. (2011). The ABCmod conceptual modeling framework. In S. Robinson, R. Brooks, K. Kotiadis, & D.-J. van der Zee (Eds.) *Conceptual Modeling for Discrete-Event Simulation* (pp. 133-178). CRC Press, Taylor & Francis Group. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.475.6964&rep=rep1&type=pdf#page=143

Arbulu, R. J., Tommelein, I. D., Walsh, K. D., & Hershauer, J. C. (2002). CEPM 3: Contributors to lead time in construction supply chains: Case of pipe supports used in power plants. *Proceedings of the Symposium of the 34th Winter Simulation Conference: 'Exploring new frontiers'.*

Ashley, D. B. (1980). Simulation of repetitive-unit construction. *Journal of the Construction Division, 106*(2), 185-194.

Babbie, E. (1990). *Survey research methods*: Wadsworth, Belmont, CA.

Bakry, I., Moselhi, O., & Zayed, T. (2013). *Fuzzy scheduling of repetitive construction projects* (pp. 1172-1176). http://www.iaarc.org/publications/fulltext/isarc2013Paper164.pdf

Balci, O. (1994). Validation, verification, and testing techniques throughout the life cycle of a simulation study. *Annals of Operations Research, 53*(1), 121-173.

Balci, O. (2001). A methodology for certification of modeling and simulation applications. *ACM Transactions on Modeling and Computer Simulation (TOMACS), 11*(4), 352-377.

Bankes, S. (1993). Exploratory modeling for policy analysis. *Operations Research, 41*(3), 435-449.

Banks, J. (1998). *Handbook of simulation: Principles, methodology, advances, applications, and practice*: John Wiley & Sons.

Barzun, J., & Graff, H. (1985). *The modern researcher*. New York: Harcourt Brace Jovanovich.

Baskerville, R. L., & Wood-Harper, A. T. (1996). A critical perspective on action research as a method for information systems research. *Journal of Information Technology, 11*(3), 235-246.

BBNZ (Building a Better New Zealand). (2011). *Building a Better New Zealand*. Retrieved from http://www.buildingabetternewzealand.co.nz/

BCSPT (Building and Construction Sector Productivity Taskforce). (2009). *A modern efficient and productive New Zealand built infrastructure industry*. Report of the Building and Construction Sector Productivity Taskforce, Department of Building and Housing, Wellington, New Zealand.

Benbasat, I., Goldstein, D. K., & Mead, M. (1987). The case research strategy in studies of information systems. *MIS Quarterly, 11*(3), 369-386.

Birtwistle, G., Luker, P., Lomow, G., & Unger, B. (1985). Process style packages for discrete event modelling: Experience from the transaction, activity, and event approaches. *Transactions of the Society for Computer Simulation, 2*(1), 25-56.

Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal, 9*(2), 27-40.

Brooks, R. J. (2010). Complexity, level of detail, and model performance. In S. Robinson, R. Brooks, K. Kotiadis, & D.-J. van der Zee (Eds.) *Conceptual Modeling for Discrete-Event Simulation* (p. 31). CRC Press, Taylor & Francis Group. http://www.crcnetbase.com/doi/abs/10.1201/9781439810385-c2

Brooks, R. J., & Tobias, A. M. (1996). Choosing the best model: Level of detail, complexity, and model performance. *Mathematical and Computer Modelling, 24*(4), 1-14.

Burrell, G., & Morgan, G. (1979). *Sociological paradigms and organisational analysis* (Vol. 248): London: Heinemann.

Campbell, D. T., & Stanley, J. C. (2015). *Experimental and quasi-experimental designs for research*: Ravenio Books.

Carr, R. I. (1979). Simulation of construction project duration. *Journal of the Construction Division*, *105*(2), 117-128.

Carson, J. S. (1986). Simulation Series. 2. Convincing Users of Models Validity is Challenging Aspect of Modelers Job. *Industrial Engineering, 18*(6), 74-85.

Cepeda, G., & Martin, D. (2005). A review of case studies publishing in Management Decision 2003-2004: Guides and criteria for achieving quality in qualitative research. *Management Decision, 43*(6), 851-876.

Chan, W.-H., & Lu, M. (2012). Construction operations simulation under structural adequacy constraints: The Stonecutters Bridge case study. *Proceedings of the Symposium of the Winter Simulation Conference (WSC),* Institute of Electrical and Electronics Engineers (IEEE).

Chang, D. (1986). *RESQUE*. University of Michigan, Ann Arbor, Mich.

Cheng, T.-m., & Feng, C.-w. (2003). An effective simulation mechanism for construction operations. *Automation in Construction, 12*(3), 227-244. doi: 10.1016/s0926-5805(02)00086-9

Chua, W. F. (1986). Radical developments in accounting thought. *Accounting Review*, *61*(4), 601-632.

Chwif, L., Barretto, M., & Paul, R. (2000). On simulation model complexity. *Proceedings of the Symposium of the Winter Simulation Conference*, Society for Computer Simulation International.

Collis, J., & Hussey, R. (2013). *Business research: A practical guide for undergraduate and postgraduate students*. Palgrave Macmillan.

Cor, H., & Martinez, J. C. (1999). A case study in the quantification of a change in the conditions of a highway construction operation. *Proceedings of the Symposium of the 31st Winter Simulation Conference: "Simulation---a bridge to the future"* (Vol. 2), ACM.

Coughlan, P., & Coghlan, D. (2002). Action research for operations management. *International Journal of Operations & Production Management, 22*(2), 220-240. doi: 10.1108/01443570210417515

Creswell, J. W. (1994). *Research design: Qualitative and quantitative*. London. Sage.

Creswell, J. W. (2009). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage Publications.

Creswell, J. W., & Miller, D. L. (2000). Determining validity in qualitative inquiry. *Theory into Practice, 39*(3), 124-130.

Crotty, M. (1998). *The foundations of social research: Meaning and perspective in the research process*. Sage.

Darke, P., Shanks, G., & Broadbent, M. (1998). Successfully completing case study research: Combining rigour, relevance and pragmatism. *Information Systems Journal, 8*(4), 273-289.

Davies, R., Roderick, P., & Raftery, J. (2003). The evaluation of disease prevention and treatment using simulation models. *European Journal of Operational Research, 150*(1), 53-66.
DeMarrais, K., & Lapan, S. D. (2003). *Foundations for research: Methods of inquiry in education and the social sciences*: Routledge.
DeWalt, K. M., & DeWalt, B. R. (2010). *Participant observation: A guide for fieldworkers*: Rowman Altamira.
Dion, D. (2003). Evidence and inference in the comparative case study. In *Necessary conditions: Theory, Methodology, and Applications* (pp. 95-112). https://www.jstor.org/stable/422284?seq=1#page_scan_tab_contents
Easterby-Smith, M. T., Thorpe R., & Lowe A. (1991). *Management research: An introduction, 1*. Sage: London.
EasyFit. (n.d.). Mathwave data analysis & simulation. http://www.mathwave.com/en/home.html
Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review, 14*(4), 532-550.
El Ghandour, W. (2007). *Integrated information-based construction simulation system*. ProQuest, UMI Dissertations Publishing.
Evans, J. B. (1988). *Structures of discrete event simulation: An introduction to the engagement strategy*. Halsted Press.
Fellows, R., & Liu, A. (2003). *Research methods for construction*. Malden, MA: Blackwell Science. Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwY2BQSAVWuYnmycaGKcmGhommSaZAVUlGyaYpKRYpoAPwUMZzkUpzNyEGptQ8UQZJN9cQZw_dxNKSeOgYRry5ObBmMjYSY-BNBC38zisBbxBLkWBQALYOzczNUsxNTdKANXuyWZKxRWIKsA5MNDBJTEpOsZAEHaCDbpAkgzSyIGyiJ97ICNgEsMAtCzQXt17Q0XZmAIMbSLw
Filippini, R. (1997). Operations management research: Some reflections on evolution, models and empirical studies in OM. *International Journal of Operations & Production Management, 17*(7), 655-670.
Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry, 12*(2), 219-245.
Forza, C. (2002). Survey research in operations management: A process-based perspective. *International Journal of Operations & Production Management, 22*(2), 152-194.
Fu, J. (2013). *Logistics of earthmoving operations: Simulation and optimization*. KTH. http://www.diva-portal.org/smash/get/diva2:623911/FULLTEXT01.pdf
Fulenwider, M. (2002). *Dynamic planning and control for large scale infrastructure projects: Route 3N as a case study*. Massachusetts Institute of Technology (MIT).
Gable, G. G. (1994). Integrating case study and survey research methods: An example in information systems. *European Journal of Information Systems, 3*(2), 112-126.
Gass, S. I., & Joel, L. S. (1981). Concepts of model confidence. *Computers & Operations Research, 8*(4), 341-346.
Gerring, J. (2006). *Case study research: Principles and practices*. Cambridge University Press.
Glock, C. Y., & Bennett, J. (1967). *Survey research in the social sciences*. Russell Sage Foundation.
Gray, D. E. (2009). *Doing research in the real world*. London: SAGE. Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwY2BQSAVWu

YnmycaGKcmGhommSaZAVUlGyaYpKRYpoAPwUMZzkUpzNyEGptQ8UQYpN9cQZw_dxNKSeOgYRjzojBBgxWkkxsCbCFr5nVcC3iGWIsGgYJJmnJYMzLfJ5hZmJgZJlklmycZJFqaJiakWBsmmZmmSDMJYTJJkkEYWhU31xANTsLGpMQBCbTWe

Guba, E. G., & Lincoln, Y. S. (1994). Competing paradigms in qualitative research. In E. G. Guba & Y. S. Lincoln (Eds.) *Handbook of qualitative research (*Vol. 2), 163-194.

Hajjar, D. (1999). *A unified modeling methodology for simulation-based planning of construction projects*. ProQuest, UMI Dissertations Publishing.

Hajjar, D., & AbouRizk, S. (1998). Modeling and analysis of aggregate production operations. *Journal of Construction Engineering and Management*, *124*(5), 390-401. doi: 10.1061/(ASCE)0733-9364(1998)124:5(390)

Hajjar, D., & AbouRizk, S. (1999). Simphony: An environment for building special purpose construction simulation tools. Retrieved from http://aut.summon.serialssolutions.com/link/0/eLvHCXMwY2BQSElOBlbCKcC6LNnULNU4OdXALNXQNC0VmDiSU5KSjFHGc5FKczchBqbUPFEGFTfXEGcPXdBlJ_EFkDMX4g3ArRkzEwsD4zQDE8NEQzEG3kTQGvC8EvBesRRxBtY0YISlioMKUXGggeIMHBGWRkF-EZYBEK4QjKtXDN7QpFdYIg4ss8HxrWuoZwoAde4uCg doi:10.1109/WSC.1999.816811

Hajjar, D., & AbouRizk, S. (2002). Unified modeling methodology for construction simulation. *Journal of Construction Engineering and Management*, *128*(2), 174-185. doi: 10.1061/(ASCE)0733-9364(2002)128:2(174)

Halpin, D. (1977). CYCLONE-method for modeling job site processes. *Journal of the Construction Division*, *103*(ASCE 13234 Proceeding).

Halpin, D. (1990). *Micro-CYCLONE user's mannual*. Purdue University, West Lafayette, IN.

Halpin, D., & Riggs, L. S. (1992). *Planning and analysis of construction operations* (p. 381), John Wiley and Sons, Inc: New York, NY.

Halpin, D., & Woodhead, R. (1976). *Design of construction and process operations*. Wiley: New York

Hammersley, M., & Atkinson, P. (2007). *Ethnography: Principles in practice*. Routledge.

Hassan, M. M., & Gruber, S. (2008). Simulation of concrete paving operations on Interstate-74. *Journal of Construction Engineering and Management*, *134*(1), 2-9. doi: 10.1061/(ASCE)0733-9364(2008)134:1(2)

Hassanein, A. (2003). *Planning and scheduling highway construction using GIS and dynamic programming*. PhD thesis, Concordia University, Montreal. http://spectrum.library.concordia.ca/2141/1/NQ77904.pdf

Hassanein, A., & Moselhi, O. (2004). Planning and scheduling highway construction. *Journal of Construction Engineering and Management*, *130*(5), 638-646. doi: 10.1061/(ASCE)0733-9364(2004)130:5(638)

Hays, P. A. (2004). Case study research. In *Foundations for research: Methods of inquiry in education and the social sciences* (pp. 217-234). https://books.google.co.nz/books?hl=en&lr=&id=SbCPAgAAQBAJ&oi=fnd&pg=PA217&dq=Case+study+research+Hays,+P.+A.+2004&ots=B1HRf8Se3o&sig=0ubtCqt

Henriksen, J. (1989). Alternative modeling perspectives: Finding the creative spark. In *Proceedings of the ACM Winter Simulation Conference*, Washington, DC, 8-10 Dec. Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwhV3NS8MwFA_iSRCcOPET8g90tslL2goexnB4ETzsPtKXvIvrGHPz7_clq50ywWPSEtI0yfu

9r98TQlLlyCLjAOWwBI--aWxVWQ11Qbpx8Nue2xMk-QUP0SbvPXb81COkNnpKGROnZHFd6siPP5689naU3BjegrF6E0u-gu9bbnbEOt9t3eXlFWAeyljlcpTGi_II2x_SZHrWx2EdRpEckDT-N92BGO6T9uRbL47OxVFYXoin8aKz-H0Gmare8DO52mdYfjzK5LbmXoaCcoch-V2-aNbvQzGbPs8mL1lXMSFzDGsyVhUAgbCsQwWGMDQ1aT6UREiKcgisrEU3IxlXF8p6rTwjNhXqyjpNvtKX4tTFwPrlJiXg-SshIZ56BDRB50DWOVYoARU674pgKFyLAS_DfLXjxpinT7_5o-9WnKTwrBQHdyeON-ttuOc_sN18AS94nKA doi: 10.1145/76738.76821

Herriott, R. E., & Firestone, W. A. (1983). Multisite qualitative policy research: Optimizing description and generalizability. *Educational Researcher, 12*(2), 14-19.

Hills, P. (1971). *Hocus*. PE Group: Egham, Surrey, UK.

Hodges, J. S. (1991). Six (or so) things you can do with a bad model. *Operations Research, 39*(3), 355-365.

Holden, M. T., & Lynch, P. (2004). Choosing the appropriate methodology: Understanding research philosophy. *The Marketing Review, 4*(4), 397-409.

Holmes, A. (2013). Direct observation. In F. R. Volkmar (Ed.), *Encyclopedia of Autism Spectrum Disorders* (pp. 980-981), Springer: New York. doi: 10.1007/978-1-4419-1698-3_1758

Hooper, J. W. (1986). Strategy-related characteristics of discrete-event languages and models. *Simulation, 46*(4), 153-159.

Hooper, J. W., & Reilly, K. D. (1982). An algorithmic analysis of simulation strategies. *International Journal of Computer & Information Sciences, 11*(2), 101-122.

Houser, J. (2013). *Nursing research: Reading, using and creating evidence*: Jones & Bartlett Publishers.

Howe, K. R. (2009). Positivist dogmas, rhetoric, and the education science question. *Educational Researcher, 38*(6), 428-440.

Hsie, M., Chang, C.-J., Yang, I. T., & Huang, C.-Y. (2009). Resource-constrained scheduling for continuous repetitive projects with time-based production units. *Automation in Construction, 18*(7), 942-949. doi: 10.1016/j.autcon.2009.04.006

Huang, R., Grigoriadis, A. M., & Halpin, D. (1994). Simulation of cable-stayed bridges using DISCO. *Proceedings of the Symposium of the Winter Simulation Conference*, Institute of Electrical and Electronics Engineers (IEEE), Piscataway, NJ.

Hughes, J. A., & Sharrock, W. W. (1997). *The philosophy of social research* (3rd edn). Routledge. ISBN-10: 0582311055, ISBN-13: 978-0582311053

Innis, G., & Rexstad, E. (1983). Simulation model simplification techniques. *Simulation, 41*(1), 7-15. doi: 10.1177/003754978304100101

Ioannou, P. G. (1999). Construction of a dam embankment with nonstationary queues. *Proceedings of the Symposium of the 31st Winter Simulation Conference: "Simulation—a bridge to the future"* (Vol. 2), ACM.

Ioannou, P. G., & Martinez, J. C. (1996). Comparison of construction alternatives using matched simulation experiments. *Journal of Construction Engineering and Management, 122*(3), 231-241.

Ioannou, P. G., & Martinez, J. (1998). Project scheduling using state-based probabilistic decision networks. *Proceedings of the Symposium of the 30th Winter Simulation Conference*, IEEE [Institute of Electrical and Electronics Engineers] Computer Society Press.

Ioannou, P. G., & Martinez, J. C. (1999). Who serves whom? Dynamic resource matching in an activity-scanning simulation system. *Proceedings of the*

Symposium of the 31st Winter Simulation Conference: "Simulation—a bridge to the future" (Vol. 2), ACM.

Johnson, T. H. (1998). Mission space model development, reuse and the conceptual models of the mission space toolset. Paper presented at the *Symposium of the 1998 Spring Simulation Interoperability Workshop*.

Johnston, W. J., Leach, M. P., & Liu, A. H. (1999). Theory testing using case studies in business-to-business research. *Industrial Marketing Management, 28*(3), 201-213.

Jorgensens, D. L. (1989). *Participant observation: A methodology for human studies*. Sage.

Kamat, V. R., & Martinez, J. (2003). Validating complex construction simulation models using 3D visualization. *Systems Analysis Modelling Simulation*, *43*(4), 455-467.

Kannan, G. (1999). *A methodology for the development of a production experience database for earthmoving operations using automated data collection*. Virginia Polytechnic Institute and State University.

Kerlinger, F. N. (1986). *Foundations of Behavioral Research*: Harcourt Brace Jovanovich College Publishers: New York, NY.

Kim, J. (2007). *An investigation of activity duration input modeling by duration variance ratio for simulation-based construction scheduling*. PhD thesis, Rutgers University/The State University of New Jersey–New Brunswick, New Brunswick, NJ.

Kim, K. J. (1997). *Simplified discrete event simulation for heavy construction operations*. ProQuest, UMI Dissertations Publishing. Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwY2BQMLVMMTdMAdZLKYnmKSaGacA0kmaRapGSAkzLJkmWaSjjuUiluZsQA1NqniiDrJtriLOHLqxojE_JyYk3NwZWlRZmFoaGYgy8iaDF33kl4E1iKeIMrGnAmEoVB5We4kCTxBk4IizDQy0ivf0gXCEYV68YvJNJr7BEHFhYgyNa11jPAAABeCwn

Kim, S. (2003). Research paradigms in organizational learning and performance: Competing modes of inquiry. *Information Technology, Learning, and Performance Journal*, *21*(1), 9.

Kock, N., Gallivan, M. J., & DeLuca, D. (2008). Furthering information systems action research: A post-positivist synthesis of four dialectics. *Journal of the Association for Information Systems*, *9*(2), 4.

Kock Jr, N. F., McQueen, R. J., & Scott, J. L. (1997). Can action research be made more rigorous in a positivist sense? The contribution of an iterative approach. *Journal of Systems and Information Technology*, *1*(1), 1-23.

LeCompte, M. D., & Schensul, J. J. (2010). *Designing and conducting ethnographic research* (Vol. 1). Rowman Altamira.

Lee, A. S. (1989). A scientific methodology for MIS case studies. *MIS Quarterly*, *(13)*1, 33-50. https://www.jstor.org/stable/248698?seq=1#page_scan_tab_contents

Leonard-Barton, D. (1990). A dual methodology for case studies: Synergistic use of a longitudinal single site with replicated multiple sites. *Organization Science, 1*(3), 248-266.

Lijphart, A. (1975). The comparable-cases strategy in comparative research. *Comparative Political Studies*, *8*(2), 158.

Liu, L. Y. (1995). Simulating construction operations of precast-concrete parking structures. *Proceedings of the Symposium of the 27th Winter Simulation Conference*, Institute of Electrical and Electronics Engineers (IEEE) Computer Society.

Liu, L. Y., & Ioannou, P. G. (1992). Graphical object-oriented discrete-event simulation system. *Proceedings of the Symposium of the 1992 Winter Simulation Conference*, Institute of Electrical and Electronics Engineers (IEEE), Piscataway, NJ.

Lluch, J., & Halpin, D. (1982). Construction operation and microcomputers. *Journal of the Construction Division*, *108*(1), 129-145.

Love, P. E., Holt, G. D., & Li, H. (2002). Triangulation in construction management research. *Engineering Construction and Architectural Management*, *9*(4), 294-303.

Lu, M. (2003). Simplified discrete-event simulation approach for construction simulation. *Journal of Construction Engineering and Management*, *129*(5), 537-546. doi: 10.1061/(ASCE)0733-9364(2003)129:5(537)

Lucas, T. W., & McGunnigle, J. E. (2003). When is model complexity too much? Illustrating the benefits of simple models with Hughes' salvo equations. *Naval Research Logistics (NRL)*, *50*(3), 197-217. doi: 10.1002/nav.10062

Lucko, G. (2008). Productivity scheduling method compared to linear and repetitive project scheduling methods. *Journal of Construction Engineering and Management*, *134*(9), 711-720. doi: 10.1061/(ASCE)0733-9364(2008)134:9(711)

MacDonald, C., & Gunn, E. A. (2012). Allocation of simulation effort for neural network vs. regression metamodels. *Proceedings of the Symposium of the Winter Simulation Conference.*

Malhotra, M. K., & Grover, V. (1998). An assessment of survey research in POM: From constructs to theory. *Journal of Operations Management*, *16*(4), 407-425.

Mangan, J., Lalwani, C., & Gardner, B. (2004). Combining quantitative and qualitative methodologies in logistics research. *International Journal of Physical Distribution & Logistics Management*, *34*(7), 565-578.

Marshall, C., & Rossman, G. B. (2014). *Designing qualitative research*. Sage Publications.

Martinez, J. (1996). *Stroboscope: State and resource based simulation of construction processes*. University of Michigan.

Martinez, J. (1998a). *Earthmover-simulation tool for earthwork planning*. IEEE [Institute of Electrical and Electronics Engineers] Computer Society Press. Retrieved from http://aut.summon.serialssolutions.com/link/0/eLvHCXMwTV27DsIwDIwQAwtLJcjKD6RKk7pJZkTFhBAwdHVeYyWg_D9uC4jRk5fT6c66kxnbSTQmyCo0MUUFNuusUdZIwjn7xs9J998994_N24ItUr9h1_Zw2x_F5xmAwBpqQbLXWS1TQBOU1NpjHg2VswpJMUPMFSBZD0uABZsMRp0hgWoiBpnJFGzZGsfIeD9M1bLI2XJ4vBIfKZfTes5WnVOXU-fO81h8x_I51Z_K-8CJ4Sd0iKqEN88FOGM

Martinez, J. (1998b). EZStrobe: General-purpose simulation system based on activity cycle diagrams. *Proceedings of the Symposium of the Winter Simulation Conference*, Institute of Electrical and Electronics Engineers (IEEE).

Martinez, J. (2001). EZStrobe: General-purpose simulation system based on activity cycle diagrams. *Proceedings of the Symposium of the 33rd Winter Simulation Conference*. Institute of Electrical and Electronics Engineers (IEEE) Computer Society.

Martinez, J., & Ioannou, P. (1994). General purpose simulation with STROBOSCOPE. *Society for Computer Simulation International*. Retrieved from http://aut.summon.serialssolutions.com/link/0/eLvHCXMwVV09CwIxDC2C4OJyoF39Az16H2nNLB5OInLDrb00HQ_E-_-Yngo6Zgs0vPcS8lKlDkDgkKnJ7t_QCt8RRCSbXHT5YBn8zXN_0Lwr1Iqnneq

7c3-6mM9nACa0vjHJRlEuENi27AGrUXQ8Ou-lYIFri5xGEWCW0Iu-J2FF5KN0Xx5SFI6jsdqrbcg749O8eMuiVuskD8w6g66WBLTaDFjfrwPe3mHxDcvnYoAqH7MWjF_qw1QlvACZpTfn doi: 10.1109/WSC.1994.717503

Martinez, J., & Ioannou, P. G. (1996). State-based probabilistic scheduling using STROBOSCOPE’s CPM add-on. *Proceedings of the 5th Construction Congress*, American Society of Civil Engineers (ASCE), Reston, VA, 438-445.

Martinez, J., & Ioannou, P. G. (1999). General-purpose systems for effective construction simulation. *Journal of Construction Engineering and Management, 125*(4), 265-276. doi: 10.1061/(ASCE)0733-9364(1999)125:4(265)

Marzouk, M. (2002). *Optimizing earthmoving operations using computer simulation*. Concordia University.

Marzouk, M. (2010). The state of computer simulation applications in construction. In In E. Abu-Taieh, & A. El-Sheikh (Eds.), *Handbook of research on discrete event simulation environments: Technologies and applications* (pp. 509-534). Hershey, PA: IGI Global. doi:10.4018/978-1-60566-774-4.ch022

Marzouk, M., El-Dein, H. Z., & El-Said, M. (2007). Application of computer simulation to construction of incremental launching bridges. *Journal of Civil Engineering and Management, 13*(1), 27-36.

Marzouk, M., Said, H., & El-Said, M. (2008). Special-purpose simulation model for balanced cantilever bridges. *Journal of Bridge Engineering, 13*(2), 122-131.

Marzouk, M., Said, H., & El-Said, M. (2009). Framework for multiobjective optimization of launching girder bridges. *Journal of Construction Engineering and Management, 135*(8), 791-800.

Marzouk, M., El-Dein, H. Z., & El-Said, M. (2006). Bridge_Sim: Framework for planning and optimizing bridge deck construction using computer simulation. *Proceedings of the Symposium of the Winter Simulation Conference (WSC 06),* Institute of Electrical and Electronics Engineers (IEEE).

Mawdesley, M. J., Askew, W. H., & Al-Jibouri, S. H. (2004). Site layout for earthworks in road projects. *Engineering, Construction and Architectural Management, 11*(2), 83-89.

McCutcheon, D. M., & Meredith, J. R. (1993). Conducting case study research in operations management. *Journal of Operations Management, 11*(3), 239-256.

Meredith, J. R. (1998). Building operations management theory through case and field research. *Journal of Operations Management, 16*(4), 441-454. doi: 10.1016/S0272-6963(98)00023-0

Meredith, J. R., Raturi, A., Amoako-Gyampah, K., & Kaplan, B. (1989). Alternative research paradigms in operations. *Journal of Operations Management, 8*(4), 297-326.

Miles, M. B., & Huberman, A. M. (1984). *Qualitative data analysis: A sourcebook of new methods*. Sage Publications. ISBN-10: 0803922744, ISBN-13: 978-0803922747. https://www.amazon.com/Qualitative-Data-Analysis-Sourcebook-Methods/dp/0803922744

Mohamed, Y. (2002). *A framework for systematic improvement of construction systems*. University of Alberta.

Mohamed, Y., & AbouRizk, S. (2005). Framework for building intelligent simulation models of construction operations. *Journal of Computing in Civil Engineering, 19*(3), 277-291. doi: 10.1061/(ASCE)0887-3801(2005)19:3(277)

Morgan, G., & Smircich, L. (1980). The case for qualitative research. *Academy of Management Review, 5*(4), 491-500.

Morrison, G. R., Ross, S. M., & Kemp, J. E. (2004). *Design effective instruction*. New York: John Wiley & Sons.

Musselman, K. J. (1992). Conducting a successful simulation project. *Proceedings of the Symposium of the 24th Winter Simulation Conference.* ACM.
Musselman, K. J. (1998). Guidelines for success. In J. Banks (Ed.) *Handbook of simulation: principles, methodology, advances, applications, and practice* (pp. 719-743). http://au.wiley.com/WileyCDA/WileyTitle/productCd-0471134031.html#see-less-toc
Myers, M. D. (2013). *Qualitative research in business and management*. Sage.
Nance, R. E. (1994). The conical methodology and the evolution of simulation model development. *Annals of Operations Research, 53*(1), 1-45. doi: 10.1007/BF02136825
Neuman, S. B., & Celano, D. (2001). Access to print in low-income and middle-income communities: An ecological study of four neighborhoods. *Reading Research Quarterly, 36*(1), 8-26.
Nikakhtar, A., Hosseini, A. A., & Wong, K. Y. (2012). Sensitivity analysis of construction processes using computer simulation: A case study. *Advanced Science Letters, 13*(1), 680-684.
Nikakhtar, A., Hosseini, A. A., Wong, K. Y., & Zavichi, A. (2015). Application of lean construction principles to reduce construction process waste using computer simulation: A case study. *International Journal of Services and Operations Management, 20*(4), 461-480.
Nikakhtar, A., Wong, K. Y., Zarei, M. H., & Memari, A. (2011). Comparison of two simulation software for modeling a construction process. *Symposium of the Third International Conference on Computational Intelligence, Modelling & Simulation*, Institute of Electrical and Electronics Engineers (IEEE).
Nonaka, I., & Peltokorpi, V. (2006). Objectivity and subjectivity in knowledge management: A review of 20 top articles. *Knowledge and Process Management, 13*(2), 73-82.
Nwokah, N. G., Kiabel, B. D., & Briggs, A. E. (2009). Philosophical foundations and research relevance: Issues for marketing information research. *European Journal of Scientific Research, 33*(3), 429-437.
NZ Transport Agency. (2016). *Waterview Connection*. Retrieved May 2016, from https://www.nzta.govt.nz/projects/the-western-ring-route/waterview-connection/
Onggo, S. (2010). Methods for conceptual model representation. In S. Robinson, R. Brooks, K. Kotiadis, & D.-J. van der Zee, (Eds.), *Conceptual Modelling for Discrete-Event Simulation* (pp. 337-354). CRC Press, Taylor & Francis Group.
Ören, T. I. (1981). Concepts and criteria to assess acceptability of simulation studies: A frame of reference. *Communications of the ACM, 24*(4), 180-189.
Ören, T. I. (1984). Quality assurance in modelling and simulation: A taxonomy. In *Simulation and model-based methodologies: An integrative view* (pp. 477-517). Springer.
Orlikowski, W. J., & Baroudi, J. J. (1991). Studying information technology in organizations: Research approaches and assumptions. *Information Systems Research, 2*(1), 1-28.
Pace, D. K. (2000). Ideas about simulation conceptual model development. *Johns Hopkins APL [Applied Physics Laboratory] Technical Digest, 21*(3), 327-336.
Palaniappan, S., Sawhney, A., & Sarjoughian, H. (2006). Application of the DEVS framework in construction simulation. *Proceedings of the Winter Simulation Conference.* Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwjV1LS8NAEF5EQQShttb6hP0DCdnsIwl4KbFF0EDBIqWXstkH9NCqtP5_J8kmEZuDhxwmh2HZ3eGbb-eFEOYmElYDEElpIsk1VywTDJt45zk4s97blOo7vxNqTZlBF-

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Paulson Jr, B. C., Chan, W. T., & Koo, C. C. (1987). Construction operations simulation by microcomputer. *Journal of Construction Engineering and Management*, *113*(2), 302-314.

Peña-Mora, F., & Park, M. (1999). *Robust control of cost impact on fast-tracking building construction projects*. Massachusetts Institute of Technology (MIT).

Peña-Mora, F., & Park, M. (2001). Dynamic planning for fast-tracking building construction projects. *Journal of Construction Engineering and Management, 127*(6), 445-456.

Pidd, M. (2003). *Tools for thinking: Modelling in management science*. Hoboken, NJ: Wiley. Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwjV09C8IwED38ABEcrB9Yq9A_IMSSmnQWi6tQcCxJk-AgdtD_j5e0ERUHxwRyJCHk3ru8uwDEwpKuVDO5yxThzFScGi65pjJJFdfmM54L_gdHq9j47xEGUXRCu0i0Mkd4zqdXVMVWyCK2Xt-QUEbw5kX478vstG1q_ZDP6XNeJB9Dz2YWBNDRtwkMvOR8CkFR19d7jPAxflyavwxmEOaHYn_coI2yDbGUzYySOYyE1aXfHi5_TS0gZkSKarc1yJsQ6SsikM9wxAhSKJrxSoW2vs-3oRCi906_BeUWwQFLl7-GRDB0MjMXHFhB3-Dh1Wu30iemc2rg

Pinsonneault, A., & Kraemer, K. L. (1993). Survey research methodology in management information systems: An assessment. *Journal of Management Information Systems*, *10*(2), 75-105.

Podolny, W., & Muller, J. M. (1994). *Construction and design of prestressed concrete segmental bridges*. https://trid.trb.org/view.aspx?id=387448

Poshdar, M., González, V., Raftery, G., & Orozco, F. (2014). Characterization of process variability in construction. *Journal of Construction Engineering and Management*, *140*(11), 05014009.

Pritsker, A. A. B. (1986a). *Introduction to simulation and SLAM II*. (3rd edn.) John Wiley & Sons, Inc: New York, NY. ISBN:0-470-20292-0

Pritsker, A. A. B. (1986b). Model evolution: A rotary index table case history. *Proceedings of the Symposium of the 18th Winter Simulation Conference,* ACM.

Pritsker, A. A. B. (1987). Model evolution II: An FMS design problem. *Proceedings of the Symposium of 19th Winter Simulation Conference*, ACM.

Pritsker, A. A. B., O'Reilly, J., & LaVal, D. (1997). *Simulation with Visual SLAM and AweSim*. West Lafayette, IN: Systems Publishing Corporation.

Puri, V. (2012). *Incorporation of continuous activities into activity cycle diagram based discrete event simulation for construction operations*. ProQuest, UMI Dissertations Publishing.

Robinson, S. (2001). Soft with a hard centre: Discrete-event simulation in facilitation. *Journal of the Operational Research Society, 52*(8), Part Special Issue: OR42 Papers. 905-915. https://www.jstor.org/stable/822951?seq=1#page_scan_tab_contents

Robinson, S. (2008a). Conceptual modelling for simulation Part I: Definition and requirements. *Journal of the Operational Research Society, 59*(3), 278-290. doi: 10.1057/palgrave.jors.2602368

Robinson, S. (2008b). Conceptual modelling for simulation Part II: A framework for conceptual modelling. *Journal of the Operational Research Society, 59*(3), 291-304.

Robinson, S. (2012). Tutorial: Choosing what to model—Conceptual modeling for simulation. *Proceedings of the Symposium of the Winter Simulation Conference (WSC)*, Institute of Electrical and Electronics Engineers (IEEE).

Robinson, S., Brooks, R. J., Kotiadis, K., & van der Zee, D.-J. (Eds.) (2011). *Conceptual modeling for discrete-event simulation*. Chapman and Hall/CRC Press: Boca Raton, FL. Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwY2BQSDZPTgN2cswsjRLBR4wZpxkkmqYBe8uW5sbG5uDT95DGc-HDFqAVG8RNwpiD5vqA5S6zqSW4xxMeCKpbYPv0wDWDmyADaypou4AQA1NqnjCDALRRpwDNMsVAIdi9CTAxYQZuX_hZqcUiDIbOkJ2DpYk5CuB7aYDuUAA2JRVAG2aLgG1aXfAhSwrFmbnQq7ZEGaTcXEOcPXSBjomHjr_EQ51rLMbAmwhatZ5XAt7dliLBoJBimmpmnmgGbrSYpCZZJFmYAPOUYVJqomlqmkmykSSDMBaTpLCKSjNwQcY7QUiGgaWkqDRVFhwsAPSWcns

Robinson, S., & Pidd, M. (1998). Provider and customer expectations of successful simulation projects. *Journal of the Operational Research Society*, *49*(3), 200-209. http://link.springer.com/article/10.1057/palgrave.jors.2600516

Rowley, J. (2002). Using case studies in research. *Management Research News, 25*(1), 16-27.

Russell, A. D., & Dubey, A. (1995). Resource leveling and linear scheduling. In J. P. Mohsen (Chair), *Symposium of the Second Congress of Computing in Civil Engineering,* American Society of Civil Engineers (ASCE), Nashville, TN.

Said, H., Marzouk, M., & El-Said, M. (2009). Application of computer simulation to bridge deck construction: Case study. *Automation in Construction, 18*(4), 377-385. doi: 10.1016/j.autcon.2008.11.004

Salt, J. (1993). Simulation should be easy and fun. *Symposium of the Winter Simulation Conference*, ACM. doi: 10.1145/256563.256567

Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research methods for business students*. Harlow: Prentice Hall.

Sawhney, A. (1994). *Simulation-based planning for construction*. ProQuest, UMI Dissertations Publishing. Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwnV1LawIxEB7aepEWrFWxPiBnYem668Tdkwcf9V7vskl2oeAT9f87syaorL30GAJhIMl830wm3wAIgiSFiryeiQMtmbEa7EvUOvMxkqju87ngJCDs1jqPmLtps9WcIf8KhhgP_DCUo93e45ZR_LRq-2c8Q4lxn4_09y33uYbqIWE2Es-PrOKOG_cLDjhHlVkFXIFosZqkINb4X7Pf4XVy8-Rehad08wEVSz6FvdqHGvR-fte2lZfH0GbEzvYzEsRrhd5epWbr0J1NF-O556xZmtVqSdEvEbuI4KoBbwkXzm-O-Qc70wQR-HGKmfbDjMlJSgExUYQkGKpMJVpK_ITG48Vaf020oXwRHOY8RQdeyLi0S9h_Op4BwMSdzQ

Sawhney, A., & AbouRizk, S. (1996). Computerized tool for hierarchical simulation modeling. *Journal of Computing in Civil Engineering*, *10*(2), 115-124. doi: 10.1061/(ASCE)0887-3801(1996)10:2(115)

Sawhney, A., AbouRizk, S., & Halpin, D. (1998). Construction project simulation using CYCLONE. *Canadian Journal of Civil Engineering*, *25*(1), 16-25. doi: 10.1139/cjce-25-1-16

Scholz, R. W., & Tietje, O. (2002). *Embedded case study methods: Integrating quantitative and qualitative knowledge*. Sage.

Schruben, L. (1992). *SIGMA: A graphical simulation modeling program*. Boyd and Fraser Publishing Company: Danvers, MA.

Schruben, L., & Yücesan, E. (1993). Modeling paradigms for discrete event simulation. *Operations Research Letters, 13*(5), 265-275. doi: 10.1016/0167-6377(93)90049-M

Seidman, I. (2013). *Interviewing as qualitative research: A guide for researchers in education and the social sciences*: Teachers College Press.

Seymour, D., Crook, D., & Rooke, J. (1997). The role of theory in construction management: A call for debate. *Construction Management & Economics, 15*(1), 117-119.

Shannon, R. E. (1992). Introduction to simulation. *Proceedings of the Symposium of the 24th Winter Simulation Conference*, ACM.

Shenton, A. K. (2004). Strategies for ensuring trustworthiness in qualitative research projects. *Education for Information, 22*(2), 63-75.

Shi, J., & AbouRizk, S. (1997). Resource-based modeling for construction simulation. *Journal of Construction Engineering and Management*, American Society of Civil Engineers (ASCE), *123*(1), 26-33.

Shi, J., & AbouRizk, S. (1998). An automated modeling system for simulating earth-moving operations. *Journal of Computer-Aided Civil and Infrastructure Engineering, 13*, 121-130.

SIS (Swarm Intelligence Symposium) Committee (2007). *IEEE Recommended Practice for High Level Architecture (HLA) Federation Development and Execution Process (FEDEP):* Institute of Electrical and Electronics Engineers (IEEE) Standard.

Sobanjo, J. O. (1999). Cost estimating under uncertainty: Issues in bridge management. *Presentations of the Symposium of the 8th International Bridge Management Conference*, Denver, CO.

Srisuwanrat, C. (2009). *The Sequence Step Algorithm: A simulation-based scheduling algorithm for repetitive projects with probabilistic activity durations*. ProQuest, UMI Dissertations Publishing.

Sterman, J. D. (1992). System dynamics modeling for project management. Unpublished manuscript, Cambridge, MA.

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world* (Vol. 19). Irwin/McGraw-Hill: Boston.

Stuart, I., McCutcheon, D., Handfield, R., McLachlin, R., & Samson, D. (2002). Effective case research in operations management: A process perspective. *Journal of Operations Management, 20*(5), 419-433.

Tam, C. (2007). *Decision making and operations research techniques for construction management*. City University of HK Press.

Tang, S., Ahmad, I. U., Ahmed, S. M., & Lu, M. (2004). *Quantitative techniques for decision making in construction: Society, literature, film* (Vol. 1). Hong Kong University Press.

Tellis, W. (1997). Application of a case study methodology. *The Qualitative Report, 3*(3), 1-17.

Thomas, A., & Charpentier, P. (2005). Reducing simulation models for scheduling manufacturing facilities. *European Journal of Operational Research, 161*(1), 111-125. doi: 10.1016/j.ejor.2003.08.042

Tocher, K. D. (1963). *The art of simulation*, English Universities Press: London, UK.

Tommelein, I. D. (1998). Pull-driven scheduling for pipe-spool installation: Simulation of lean construction technique. *Journal of Construction Engineering and Management*, *124*(4), 279-288.
Tommelein, I. D. (1999). Travel-time simulation to locate and staff temporary facilities under changing construction demand. *Proceedings of the Symposium of the 31st Winter Simulation Conference: "Simulation—a bridge to the future"* (Vol. 2), ACM.
Touran, A., & Asai, T. (1987). Simulation of tunneling operations. *Journal of Construction Engineering Management*, *113*(4), 554-568.
Ulgen, O. M., Thomasma, T., & Mao, Y. (1989). Object oriented toolkits for simulation program generators. *Proceedings of the Symposium of the 21st Winter Simulation Conference,* ACM.
van der Zee, D.-J. & van der Vorst, J. G. A. J. (2005). A modeling framework for supply chain simulation: Opportunities for improved decision making. *Decision Sciences*, *36*, 65-95. doi: 10.1111/j.1540-5915.2005.00066.x
Vorster, M., Beliveau, Y. J., & Bafna, T. (1992). Linear scheduling and visualization. *Transportation Research Record*, 1351.
Voss, C, Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management. *International Journal of Operations & Production Management, 22*(2), 195-219. doi: 10.1108/01443570210414329
Waddington, D. (2004). Participant observation. In C. Cassell & G. Symon (Eds.) *Essential guide to qualitative methods in organizational research*. London: Sage.
Walliman, N. (2006). *Social research methods*. Sage.
Wang, W.-C., & Demsetz, L. A. (2000). Model for evaluating networks under correlated uncertainty – NETCOR. *Journal of Construction Engineering and Management, 126*(6), 458-466.
Ward, S. C. (1989). Arguments for constructively simple models. *Journal of the Operational Research Society, 40*(2), 141-153. doi: 10.1057/jors.1989.19
Wedawatta, G., Ingirige, B., & Amaratunga, D. (2011). Case study as a research strategy: Investigating extreme weather resilience of construction SMEs in the UK. *Symposium of the 7th Annual International Conference of the International Institute for Infrastructure, Renewal and Reconstruction.*
Willemain, T. R. (1994). Insights on modeling from a dozen experts. *Operations Research, 42*(2), 213-222.
Willenbrock, J. H. (1972). Estimating costs of earthwork via simulation. *Journal of the Construction Engineering Division, 98*(1), 49-60.
Willits, S. D., Bettner, M., Jensen, D. E., & Coyne, M. P. (2011). Theodoric of Triple-A-Ville, accounting professor: a one-act play for a doctoral seminar. *International Journal of Critical Accounting, 3*(1), 114-121.
Wilson, J. (2014). *Essentials of business research: A guide to doing your research project*. Sage.
Wolcott, H. F. (2009). *Writing up qualitative research*. Sage: Thousand Oaks, CA.
Wu, I., Borrmann, A., Beißert, U., König, M., & Rank, E. (2010). Bridge construction schedule generation with pattern-based construction methods and constraint-based simulation. *Advanced Engineering Informatics, 24*(4), 379-388. doi: 10.1016/j.aei.2010.07.002
Wu, I., Borrmann, A., Rank, E., Beißert, U., & König, M. (2009). A pattern-based approach for facilitating schedule generation and cost analysis in bridge construction projects. *Proceedings of the Symposium of the 26th CIB-W78 Conference on Managing IT in Construction.*

Yin, R. K. (1994). *Case study research: Design and methods* (Vol. 5). Sage Publications: Thousand Oaks, CA. Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwY2BQSAVWuYnmycaGKcmGhommSaZAVUlGyaYpKRYpoAPwUMZzkUpzNyEGptQ8UQYJN9cQZw_dxNKSeOgYRrwxsFViZiTGwJsIWvedVwLeH5YiwaCQBuxjmaSlpQD7zsDyONHUwiLVLNEw0czcJDUxzTjZSJJBEMMcSQYpZDHYNE-8CbC2M8cnaQEAw6k-Kg

Yin, R. K. (2003). *Case study research: Design and methods* (Vol. 5). Sage Publications: Thousand Oaks, CA. Retrieved from http://aut.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwY2BQSAVWuYnmycaGKcmGhommSaZAVUlGyaYpKRYpoAPwUMZzkUpzNyEGptQ8UQZJN9cQZw_dxNKSeOgYBrCdCmqaGIkx8CaCFn7nlYA3iKVIMCgYGZtbmiUbGFkaJJqbmKSkWqQlphqnpSWapwDrcotEC0nQATroBkkySCMLwiZ64oGFtYWhKU5ZYNfJ2BgAmsY-5g

Yin, R. K. (2013). *Case study research: Design and methods*. Sage Publications.

Yin, R. K. (2014). *Case study research: Design and methods*. Sage Publications: Los Angeles.

Zaheer, N. (2000). *Project/process simulation modeling using discrete event construction simulation language STROBOSCOPE*. King Fahd University of Petroleum and Minerals.

Zeigler, B. P., Praehofer, H., & Kim, T. G. (1976). *Theory of modeling and simulation* (Vol. 19): John Wiley: New York.

APPENDICES

APPENDIX 1 INTRODUCTION TO EASYFIT PROGRAM (V. 5.5)

EasyFit is a data analysis and simulation application allowing the user to fit probability distributions to sample data, select the best model and apply the analysis results to make better decisions. EasyFit can be used as a stand-alone Windows application or with Microsoft Excel and other third party Excel-based simulation tools, leaving the complex technical details behind the scenes and enabling you to focus on your business goals.

Key Features

EasyFit combines the classical statistical analysis methods and innovative data analysis techniques, making it a tool of choice for anyone dealing with probability data. Product features include:

1. support for more than 50 continuous and discrete distributions;
2. powerful automated fitting mode combined with flexible manual fitting capability;
3. interactive graphs;
4. goodness of fit tests;
5. random number generation;
6. easy to use interface;
7. comprehensive Help system.

Additional Features

With EasyFit, you can:

- analyse large data sets (up to 250,000 data points);
- improve the validity of models by applying the advanced distributions;
- calculate descriptive statistics;
- enter and manipulate data using an Excel-like spreadsheet;
- organise your data and analysis results into Project Files;

- view distribution graphs and explore their properties without entering the data;
- export analysis results.

System Requirements

- Windows 7/Vista/XP/2000 or Windows Server 2008/2003;
- 20 MB available hard disk space;
- 128 MB available RAM.

EasyFit is compatible with Microsoft Excel 2010, 2007, 2003, 2002 and 2000. Note that Excel is generally not required, but if you have it installed, EasyFit will also work as an Excel add-in, in addition to being a stand-alone application.

Who Should Use EasyFit?

EasyFit is successfully used by business analysts, engineers, researchers and scientists across a wide range of industries: risk analysis, actuarial science, economics, market research, reliability engineering, hydrology, forestry, mining, medicine, image processing and many other fields dealing with random data.

Supported Distributions

EasyFit supports all the commonly used continuous distributions. Some of them have alternative names (indicated in parentheses):

• Beta	• Levy
• Burr (Burr Type 12, or Singh-Maddala)	• Laplace (Double Exponential)
• Cauchy (Lorentz)	• Logistic
• Chi-Squared	• Log-Gamma
• Dagum (Burr Type 3, or Inverse Burr)	• Log-Logistic (Fisk)
• Erlang	• Lognormal
• Error (Exponential Power, or Generalized Error)	• Nakagami (Nakagami-m)
• Error Function	• Normal (Gaussian)
• Exponential	• Pareto - first kind
	• Pareto - second kind (Lomax)

• F Distribution • Fatigue Life (Birnbaum-Saunders) • Frechet (Maximum Extreme Value Type 2) • Gamma • Generalized Gamma • Gumbel Max (Maximum Extreme Value Type 1) • Gumbel Min (Minimum Extreme Value Type 1) • Hyperbolic Secant • Inverse Gaussian • Johnson SB • Johnson SU • Kumaraswamy	• Pearson Type 5 (Inverse Gamma) • Pearson Type 6 (Beta dist. of the second kind) • Pert • Power Function • Rayleigh • Reciprocal • Rice (Ricean, or Nakagami-n) • Student's t • Triangular • Uniform • Weibull

Many distributions are available in two versions; for example, both two-parameter and three-parameter Weibull distributions are supported. In addition, seven advanced distributions are available:

• Generalized Extreme Value • Generalized Logistic • Generalized Pareto • Log-Pearson 3 (LP3)	• Phased Bi-Exponential • Phased Bi-Weibull • Wakeby

The use of advanced distributions for data analysis essentially increases the validity of models which, in turn, leads to better decisions.

The following discrete distributions are supported:

• Bernoulli • Binomial • Discrete Uniform • Geometric	• Hypergeometric • Logarithmic • Negative Binomial • Poisson

Why Use Distribution Fitting Software?

The use of probability distributions involves complex calculations that are practically impossible or very hard and time consuming to do by hand. Distribution fitting software helps you automate the data analysis and decision-making process, and enables you to focus on your core business goals rather than on technical issues.

Save Time

You can spend literally hours trying to fit a single distribution (not to mention several alternative models) to a data set using manual methods. Distribution fitting software enables you to fit a large number of distributions in seconds and compare the fitted distributions to select the best model.

Save Money and Make Better Decisions

Distribution fitting software prevents analysis errors and helps you make informed decisions based on the data available, protecting you from potential money loss.

Be More Organised and Efficient

Specialised distribution fitting software not only performs all calculations for you, but also provides an integrated environment making you more productive.

SELECTION OF THE DISTRIBUTION

Over the last decades, numerous probability distributions have been developed to address the data analysis needs in various industries, and a number of statistical methods exist to assist you in selecting the best fitting distribution.

In most cases, the method is required to fit two or more distributions, compare the results, and select the most valid model. The “candidate” distributions you fit should be chosen depending on the nature of the probability data.

To actually fit the “candidate” distributions which have been selected, the statistical methods used should allow the estimation of distribution parameters based on the sample data. The solution of this problem involves the use of certain algorithms implemented in specialised software.

After the distributions are fitted, it is necessary to determine how well the selected distributions fit the data. This can be done using the specific goodness of fit tests or visually by comparing the empirical (based on sample data) and theoretical (fitted) distribution graphs. As a result, the most valid model describing the data can be selected.

Distribution Fitting – Preliminary Steps

In the next sections, several steps are explained that the researcher should consider taking before analysing the probability data and applying the analysis results.

Step 1 – Define the Goals of Your Analysis

The very first step is to define the objectives of analysing the data. To understand the goals of the analysis, it is recommended that answers be found to the following questions:

- What kind of information would you like to obtain?
- How will you obtain the required information?
- How will you utilise that information?

The required information is the information that should be entered as simulation input data. The step to be completed here includes finding the best distribution function that can fit the data set in this research study. However, the collected data should first be prepared for distribution fitting. According to the EasyFit instructions, the analysis results significantly depend on preparing the data.

Firstly, the user of EasyFit should make sure whether or not the data format can be supported by EasyFit. The most commonly used format in probability data analysis is an unordered set of values obtained by observing some random process. The order of values in a data set is not important and does not affect the distribution fitting results. This is one of the fundamental differences between distribution fitting (and probability data analysis in general) and time series analysis where each data value is connected to a certain time point at which this value was observed.

The next step is to decide which distributions to fit. Before fitting distributions to your data, you should decide which distributions are appropriate based on the additional information about the data you have. This can be helpful to narrow your choice to a limited number of distributions before you actually perform distribution fitting.

In most cases, you do not just have raw data, you also have some additional information about the data and its properties, how the data were collected, etc. This information might be very useful to narrow your choice to several probability distributions.

In the current research study, the two factors which helped the analysis process to limit the number of probability distributions were the distributions available in the list of EZStrobe sampling functions and the nature of the data. As the data were related to the duration of operation performances, they therefore could not contain negative values.

To decide on the distribution to fit your current data, it is important to also consider your data domain. To determine the nature of the data in terms of whether it is continuous or discrete, you should answer this question: "can your data take on real values, for example, 1.5 or -2.33, or can it take on integer values?" If your data can take on real values then you should consider continuous distributions only whereas, if your data are discrete, you may want to fit both continuous and discrete distributions.

It is also recommended that continuous distribution be chosen to analyse discrete data. The reason to use continuous distribution for analysing discrete data is that there is a large number of continuous distributions which frequently provide much better fit than discrete distributions. However, if you are confident that your random data follow a certain discrete distribution, you might want to use that specific distribution rather than continuous models.

The process of analysing data using EasyFit and the selection of the probability distribution function to be fed into the EZStrobe simulated model have been presented in Section 7.1.3 and Appendix 3.

APPENDIX 2 AUTHOR’S PUBLICATIONS

Table A1 List of author’s publications

	Research Title	Key Words	Authorship Rank	Research Type	Publication Details			Date of Submission	Date of Approval	Date of Publication/ Presentation	Publication Due Date
RELATED											
1	AN ACD DIAGRAM DEVELOPED FOR SIMULATING A BRIDGE CONSTRUCTION OPERATION	Activity-Based Cycle Diagram, Bridge Construction Operation, Conceptual Model, System Behaviour, Simulating Procedure, EZStrobe	First Author	JOURNAL	International Journal of Construction Supply Chain Management		Vol. 4, Issue 2	2013	2014	2014	
2	THE POWER OF TECHNOLOGY IN BRIDGE CONSTRUCTION PROJECT MANAGEMENT	Bridge Construction, Resource Utilisation, Uncertainty, Scheduling	First Author	INTERNATIONAL CONFERENCE	International Symposium on Automation and Robotics in Construction and Mining (ISARC)	Sydney, Australia		2013	2014	2014	

3	EXPLORING THE PERFORMANCES AND THEIR INTERDEPENDENCIES IN BRIDGE CONSTRUCTION: A CASE STUDY		First Author	INTERNATIONAL CONFERENCE	Istanbul Bridge Conference	Istanbul, Turkey		2013	2014	2014	
4	SIMULATION OF BRIDGE CONSTRUCTION WORKS: AN EXPLORATORY STUDY IN NEW ZEALAND	Simulation, Repetitive, Complexity, Interdependency, Scheduling, Bridge Construction	First Author	INTERNATIONAL CONFERENCE	Sustainable Solutions in Structural Engineering and Construction (ISEC)	Bangkok, Thailand		2014	2014	2014	
5	EXPLORING POTENTIALS FOR THE APPLICATION OF SIMULATION METHODS IN CONSTRUCTION PROJECTS DELIVERY IN NEW ZEALAND		First Author	NEW ZEALAND SYMPOSIUM	New Zealand Built Environment Research Symposium (NZBERS)	Auckland, New Zealand		2014	2014	2014	
6	THE EFFECTIVENESS OF THE LAST PLANNER SYSTEM IN NEW ZEALAND CONSTRUCTION INDUSTRY: TOWARDS AN EMPIRICAL JUSTIFICATION	Construction Productivity, Last Planner System, New Zealand	Second Author	INTERNATIONAL CONFERENCE	Proceedings of the CIB World Building Congress 2016	Tampere, Finland	Vol. 1 (pp. 528-539)	2015	2015	2016	

7	IMPLEMENTATION OF THE LPS USING AN EXCEL SPREADSHEET: A CASE STUDY FROM THE NEW ZEALAND CONSTRUCTION INDUSTRY	Last Planner System, Challenges, Percent Plan Complete, Automation, Spreadsheet	First Author	JOURNAL	Construction Innovation: Information, Process, Management			2016	2017		2017
OTHERS											
8	ADVANCED ICT METHODOLOGIES (AIM) IN THE CONSTRUCTION INDUSTRY		Third Author	BOOK CHAPTER	IGI GLOBAL, USA Encyclopaedia of Information Science and Technology		4th ed.	2016	2016–2017		July 2017
9	BARRIERS TO ADOPTING BUILDING INFORMATION MODELING (BIM) WITHIN SOUTH AUSTRALIAN SMALL AND MEDIUM SIZED ENTERPRISES	Building Information Modelling (BIM), Barriers, SMEs, South Australia	Fourth Author	INTERNATIONAL CONFERENCE	Project Management Development – Practice and Participate	Fifth International Scientific Conference on Project Management in the Baltic Countries		2015	2016	2016	
10	TRUST AND INTERORGANIZATIONAL INTERACTIONS FOR MANAGING CONFLICTS IN A BLENDED TEAM	Trust, Construction Team, Construction Project	Third Author	Journal	Journal of Legal Affairs and Dispute Resolution in Engineering and Construction (ASCE)		Vol. 8, Issue 1	2015	2016	2016	

APPENDIX 3 ANIMATION ANALYSIS

As explained in Section 7.3.2, this study analysed a scenario to explore the “Animation” capability of EZStrobe. Running the simulation with the use of the “Animation” function allowed the user (the researcher) to capture the images on the changes that occurred in the state of the elements in the model. Those images are presented and described in Table A2 and in Figures A1 to A50 in this appendix.

The number given to the different captured states represented the sequence of the changes (see the first column in Table A2).

The details of the model, including name of the elements and whether of the Combi or Normal type, are represented using bold font, while a red/blue colour indicates the different states in which elements are held in the system. The next columns are included in Table A2 to help in analysing the interactions between the elements, and to describe the state of the element as well as the behaviour of the entire system.

Analysing the images helped in measuring the time required for maintaining Queues in each state. How long each of the resources was engaged in each state was therefore understood. Furthermore, the resources that should collaborate with each other in the completion of a task and their interactions during a specific period of time were identified. For example, in the completion of the BeamReadyToPick task, the resources showing in the model as working together are GntcrnRdy, BeamAvailable, Crew2Ready, Crew1Ready and Crew3Ready. Between the time that operations started (time “0”) up to almost 25 minutes, these resources are busy in the completion of the aforementioned task. The crews and other resources later changed their states to become ready for the completion of the next task, PlcBmToGround.

In this way, the “Animation” function of EZStrobe enabled the user (in this case, the researcher) to understand what the different states were, the length of the period of time of each state, and the required resources which should be engaged in each state.

In this way, the planning/management team receives a better perception of the system behaviour and different scenarios. The “Animation” function and its analysis help in understanding the system progression over the time interval, which is broken down into hours and minutes rather than per day, with this included in the development of the master schedule and the traditional planning of the operations.

Table A2 Animation analysis of scenario

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
1	**BeamRdyToPick**	0	0/0						0.00–22.93	The "0" at top left of the Combi (BeamRdyToPick) shows that none of the instances of this Combi have started yet. The "0/0" at the middle of the Combi shows that no instances have started yet since the model execution began. The blue colour indicates that the Combi is ready to start its instance.	A/ The required conditions for start of the operations are the required conditions for the start of BeamRdyToPick. All of the resources including crews, gantry crane and loaded truck should be available at gantry area to let the operations start by picking up the beam from the truck.	1

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
2	**BeamRdyToPick**	0	0/0				√	GntcrnRdy	0.0-22.93	The "0" at top left of the Combi (BeamRdyToPick) shows that none of the instances of this Combi have started yet. The "0/0" at the middle of the Combi shows that no instances have started yet since the model execution began. The blue colour indicates that the Combi is ready to start its instance.	A	2
3	**BeamRdyTo Pick**	0	0/0				√	BeamAvailable	0.0-22.93	The change of thickness of the link between BeamAvailable Queue and BeamRdyToPick indicates that Combi is starting to draw its required resources from that Queue.	A	3
4	**BeamRdyTo Pick**	0	0/0				√	Crew2Ready	0.0-22.93	The change of thickness of the link between Crew2Ready Queue and BeamRdyToPick indicates that Combi is starting to draw its required resources from that Queue.	A	4

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
5	**BeamRdyToPick**	0	0/0				√	Crew1Ready	0.0-22.93	The change of thickness of the link between BeamAvailable Queue and BeamRdyToPick indicates that Combi is starting to draw its required resources from that Queue.	A	5
6	**BeamRdyToPick**	0	0/0				√	Crew3Ready	0.0-22.93	The change of thickness of the link between BeamAvailable Queue and BeamRdyToPick indicates that Combi is starting to draw its required resources from that Queue.	A	6
7	BeamRdyToPick		1/1						0.0-22.93	The change of thickness of the link between BeamAvailable Queue and BeamRdyToPick indicates that Combi is starting to draw its required resources from that Queue.	B/ The gantry crane picks up the beam and waits for the unloaded truck to leave the gantry area.	7
8	**BeamRdyToPick**		1/1	0					0.0-22.93	The change of thickness of the link between BeamAvailable Queue and BeamRdyToPick indicates that Combi is starting to draw its required resources from that Queue.	B	8

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
9	**BeamRdyToPick**		1/1	0					0.0-22.93	The termination of BeamRdyToPick Combi allows the UnlddTrckLeavs activity to be ready to start its instance.	B	9
	UnlddTrckLeavs	0	0/0						22.93-34.72		C/ The unloaded truck leaves the gantry area. Then, the loaded gantry crane can move downward and put the beam on the ground.	
10	**BeamRdyToPick**				√				22.93-34.72	The released link between BeamRdyToPick Combi and Normal activity (UnlddTrckLeavs) becomes thick. This also indicates the dependency of the start of Normal activity on the termination of Combi.	D/ Now two main early activities are completed: the beam has been delivered to the gantry crane, and the truck has left the gantry area.	10

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	UnlddTrck Leavs								22.93-34.72		D	
11	**BeamRdyToPic k**		1/1	0		√		BmRdyFrPlc	22.93-34.72	The thickness of the released link between the BeamRdyToPick Combi and BmRdyFrPlc Queue changes which is shown: the termination of the Combi leads to releasing the resources into its associated Queue.	D	11
	UnlddTrck Leavs	0	0/0						22.93-34.72	UnlddTrckLeavs is ready to start its instance.	D	

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
12	**BeamRdyToPick**		1/1	0				**BmRdyFrPlc**	22.93-34.72	The thickness of the BmRdyFrPlc Queue changed which indicates the beam has already has been delivered from the truck to the gantry crane. Then the operation can proceed into the placement of the beam on the ground for preparation.	E/ At this step, the conditions for performing of next activity are provided. The beam is ready to be placed on the ground. The crews also are ready to work on the preparation of beam.	12
	UnlddTrck Leavs	0	0/0						22.93-34.72	UnlddTrckLeavs is ready to start its instance.	E	12
13	**BeamRdyToPic k**		1/1	0		√		Crew2Ready	22.93-34.72	The thickness of the released link between the BeamRdyToPick Combi and Crew2Ready Queue changes which is shown: the termination of the Combi leads to releasing the resources into its associated Queue.	E	13

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	UnlddTrck Leavs	0	0/0						22.93-34.72	UnlddTrckLeavs is ready to start its instance.	E	
14	**BeamRdyToPick**		1/1	0				**Crew2Ready**	22.93-34.72	When the BeamRdyToPick terminates its instance, then the associated resources to Crew2Ready should be returned.	E	14
	UnlddTrck Leavs	0	0/0						22.93-34.72	UnlddTrckLeavs is ready to start its instance.	E	
15	**BeamRdyToPick**		1/1	0		√		Crew1Ready	22.93-34.72	The thickness of the released link between the BeamRdyToPick Combi and Crew1Ready Queue changes which is shown: the termination of the Combi leads to releasing the resources into its associated Queue.	E	15

State	Combi/Normal	Number: Top Left	Number: Middle	Number: Top Right	Other changes: Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Other changes: Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Other changes: Thickness of Feeding link from Queue to Combi is changed	Other changes: The Queue involved in feeding or releasing, and resource allocating	SimTime	Description of the state	System description according to the state	Figure number
	UnlddTrckLeavs	0	0/0						22.93-34.72	UnlddTrckLeavs is ready to start its instance.	E	
16	**BeamRdyToPick**		1/1	0				**Crew1Ready**	22.93-34.72	When the BeamRdyToPick terminates its instance, then the associated resources to Crew1Ready should be returned.	E	16
16	**UnlddTrckLeavs**	0	0/0						22.93-34.72	UnlddTrckLeavs is ready to start its instance.	E	16
17	**BeamRdyToPick**		1/1	0		√		Crew3Ready	22.93-34.72	The thickness of the released link between the BeamRdyToPick Combi and Crew3Ready Queue changes which is shown: the termination of the Combi leads to releasing the resources into its associated Queue.	E	17

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	UnlddTrck Leavs	0	0/0						22.93-34.72	UnlddTrckLeavs is ready to start its instance.	E	
18	**BeamRdyToPick**		1/1	0				**Crew3Ready**	22.93-34.72	When the BeamRdyToPick terminates its instance, then the associated resources to Crew3Ready should be returned.	E	18
	UnlddTrck Leavs	0	0/0						22.93-34.72	UnlddTrckLeavs is ready to start its instance.	E	
19	**BeamRdyToPick**		1/1	0					22.93-34.72	The red colour of the BeamRdyToPick Combi shows that this activity is going to terminate its instances.	E	19
	UnlddTrckLeavs		1/1						22.93-34.72	The first “1” shows that at SimTime, one instance is taking place. And the second “1” shows that, in total, one instance of this activity has begun.	E	

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
20	BeamRdyToPick		0/1						22.93-34.72	"0" shows that no instance at SimTime is taking place. "1" shows that, in total, one instance has begun.	E	20
	UnlddTrckLeavs		1/1						22.93-34.72	The first "1" shows that at SimTime, one instance is taking place. And the second "1" shows that, in total, one instance of this activity has begun.	E	
21	BeamRdyToPick		0/1						22.93-34.72	"0" shows that no instance at SimTime is taking place. "1" shows that, in total, one instance has begun.	F/ The beam has been placed down, and it waits for preparation.	21
	UnlddTrckLeavs		1/1						22.93-34.72	The first "1" shows that at SimTime, one instance is taking place. And the second "1" shows that, in total, one instance of this activity has begun.	F	21
	PlcBmToGround	0/0	0/0						22.93-34.72	The blue border of this Combi shows that the activity is ready to start its instance(s). "0/0" indicates that no instances have been started yet.	F	21

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
22	BeamRdyToPick		0/1				√	BmRdyFrPlc	22.93-34.72	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue shows that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	22
	UnlddTrckLeavs		1/1						22.93-34.72	The first "1" shows that at SimTime, one instance is taking place. And the second "1" shows that, in total, one instance of this activity has begun.	F	
	PlcBmToGround	0/0	0/0						22.93-34.72	The blue border of this Combi shows that the activity is ready to start its instance(s). "0/0" indicates that no instances have been started yet.	F	

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
23	BeamRdyToPick		0/1				√	Crew2Ready	22.93-34.72	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue shows that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	23
	UnlddTrckLeavs		1/1						22.93-34.72	The first "1" shows that at SimTime, one instance is taking place. And the second "1" shows that, in total, one instance of this activity has begun.	F	23
	PlcBmToGround	0/0	0/0						22.93-34.72	The blue border of this Combi shows that the activity is ready to start its instance(s). "0/0" indicates that no instances have been started yet.	F	23

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
24	BeamRdyToPick		0/1				√	Crew1Ready	22.93-34.72	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue shows that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	24
	UnlddTrckLeavs		1/1						22.93-34.72	The first "1" shows that at SimTime, one instance is taking place. And the second "1" shows that, in total, one instance of this activity has begun.	F	
	PlcBmToGround	0/0	0/0						22.93-34.72	The blue border of this Combi shows that the activity is ready to start its instance(s). "0/0" indicates that no instances have been started yet.	F	

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
25	BeamRdyToPick		0/1				√	Crew3Ready	22.93-34.72	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue shows that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	25
	UnlddTrckLeavs		1/1						22.93-34.72	The first “1” shows that at SimTime, one instance is taking place. And the second “1” shows that, in total, one instance of this activity has begun.	F	25
	PlcBmToGround	0/0	0/0						22.93-34.72	The blue border of this Combi shows that the activity is ready to start its instance(s). “0/0” indicates that no instances have been started yet.	F	25

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
26	BeamRdyToPick		0/1				√	Crew1Ready	22.93-34.72	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue shows that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	26
	UnlddTrckLeavs		1/1						22.93-34.72	The first "1" shows that at SimTime, one instance is taking place. And the second "1" shows that, in total, one instance of this activity has begun.	F	
	PlcBmToGround		1/1						22.93-34.72	The changes of the colour and thickness of the border of this Combi show that the Combi has started its instance. According to the number presented at the middle top of the Combi, this Combi has started one of its instances one time.	F	

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
27	BeamRdyToPick		0/1						22.93-34.72	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue shows that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	27
	UnlddTrckLeavs		1/1						22.93-34.72	The first “1” shows that at SimTime, one instance is taking place. And the second “1” shows that, in total, one instance of this activity has begun.	F	27
	PlcBmToGround		1/1	0					22.93-34.72	The changes of the colour and thickness of the border of this Combi show that the Combi is ready to terminate its instance. It started one instance once since the model execution started.	F	27

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
28	BeamRdyToPick		0/1						22.93-34.72	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue shows that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	28
	UnlddTrckLeavs		1/1						22.93-34.72	The first "1" shows that at SimTime, one instance is taking place. And the second "1" shows that, in total, one instance of this activity has begun.	F	
	PlcBmToGround		1/1	0					22.93-34.72	The changes of the colour and thickness of the border of this Combi show that the Combi is ready to terminate its instance. It started one instance once since the model execution started.	F	

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd	0	0/0						34.72-39.76	The termination of the above Combi provides the situation for this activity to start its instance. The blue colour of the border of this activity shows that this activity is now ready to start one of its instances.	F	
29	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue shows that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	29
	UnlddTrckLeavs		1/1						34.72-39.76	The first "1" shows that at SimTime, one instance is taking place. And the second "1" shows that, in total, one instance of this activity has begun.	F	29
	PlcBmToGround		1/1	0		√			34.72-39.76	The change of the thickness of the link between Combi and Normal shows that the termination of Combi causes the Normal activity to start.	F	29

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd	0	0/0						34.72-39.76	The Normal activity is ready to start its instance(s).	F	
30	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	30
	UnlddTrckLeavs		1/1						34.72-39.76	The first “1” shows that at SimTime, one instance is taking place. And the second “1” shows that, in total, one instance of this activity has begun.	F	30
	PlcBmToGround		1/1	0					34.72-39.76	Termination of this Combi leads the next Normal activity to start its first instance.	F	30

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		1/1						34.72-39.76	The Normal activity starts one its instances one time.	F	
31	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	31
	UnlddTrckLeavs		1/1						34.72-39.76	The first "1" shows that at SimTime, one instance is taking place. And the second "1" shows that, in total, one instance of this activity has begun.	F	31
	PlcBmToGround		1/1	0					34.72-39.76	The colour and thickness of the border of the Combi changed. The termination finished. As the numbers on the top of the Combi show, this Combi has started one of its instances once since the model execution started.	F	31

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		1/1						34.72-39.76	The colour of this Normal activity changes from Blue to normal. According to the colour and numbers on the top of the activity, this activity has started one of its instances once since the model execution started.	F	
32	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	32
	UnlddTrck Leavs		1/1	0					34.72-39.76	At this time, the Normal activity is terminating its instance. By SimTime, this activity has started one of its instances once.	F	32
	PlcBmToGr ound		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	32

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		1/1						34.72-39.76	By this time, the Normal activity has started one of its instances once.	F	
33	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	33
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	33
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	33

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		1/1	0					34.72-39.76	The Normal activity is ready to terminate its instance. However, its border is shown in the red colour. In addition, the numbers on the top of the activity show that this activity has started one of its instances once since the model execution started.	F	
34	BeamRdyToPick		0/1						34.72-.39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	34
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	34
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	34

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		1/1	0		√		BmRdyFrPrprtn	34.72-39.76	By finishing the completion of Normal activity, the thickness of link between activity and Queue has changed. This shows that the outcome of the completion of the activity is going to allocate one resource unit into the next Queue.	F	
35	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	35
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	35
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	35

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		1/1						34.72-39.76	The colour of the border of the Normal activity changes to show the activity has already terminated its instance. In addition, the numbers on the top of the activity show that one of its instances has been started once since the model execution began.	F	35
36	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	36
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	36
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	36

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		1/1	0				**BmRdyFrPrprtn**	34.72-39.76	The red colour on the border of the Normal activity and the change of the thickness of the Queue show that the termination of the activity releases the resource unit(s) which should be allocated in the Queue.	F	
37	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	37
	UnlddTrckL eavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	37
	PlcBmToGr ound		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	37

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		1/1	0		√		Crew2Ready	34.72-39.76	The Normal activity is terminating its instance with its border then shown in the red colour. Also, the link between the activity and Queue called Crew2Ready is changed. This shows that the termination of activity leads to releasing the resource units to their associated Queues.	F	
38	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	38
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	38

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	38
	FnshPlcGrnd		1/1	0				**Crew2Ready**	34.72-39.76	The thickness of the border of the Queue shows that termination of the Normal activity leads to allocating the resource unit(s) into this Queue.	F	
39	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	39
	UnldTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	39

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	39
	FnshPlcGrnd		1/1	0		√		Crew3Ready	34.72-39.76	The Normal activity is terminating its instance, with its border then shown in the red colour. Also, the link between the activity and Queue called Crew3Ready is changed. This shows that the termination of activity leads to releasing the resource unit(s) to their associated Queues.	F	
40	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	40

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	40
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	40
	FnshPlcGrnd		1/1	0				**Crew3Ready**	34.72-39.76	The thickness of the border of the Queue shows that termination of the Normal activity leads to allocating the resource unit(s) into this Queue.	F	40
41	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	41

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	41
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	41
	FnshPlcGrnd		1/1	0		√		Crew1Ready	34.72-39.76	The Normal activity is terminating its instance, with its border then shown in the red colour. Also, the link between the activity and Queue called Crew1Ready is changed. This shows that the termination of activity leads to releasing the resource unit(s) to their associated Queues.	F	

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
42	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	42
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	42
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	42
	FnshPlcGrnd		1/1	0				**Crew1Ready**	34.72-29.76	The thickness of the border of the Queue shows that termination of the Normal activity leads to allocating the resource unit(s) into this Queue.	F	

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
43	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	43
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	43
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	43

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		0/1						34.72-39.76	The colour and thickness of the border of this activity changed to normal to present that the termination has already finished. The numbers also show that no instance is taking place at SimTime, while the activity has started one instance since the model execution began.	F	
44	BeamRdyToPick		0/1						34.72-39.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instanced, and is ready to release its resources into the associated Queues.	F	44
	UnlddTrckLeavs		0/1						34.72-39.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	PlcBmToGround		0/1						34.72-39.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	
	FnshPlcGrnd		0/1						34.72-39.76	This activity started one of its instances once. Also, no instances are taking place at SimTime.	F	
	Preparation	0	0/0						39.76-73.76	Allocating the resource in the BmRdyFrPrprtn leads to the required conditions for this Combi to be provided. The Combi is then ready to start its instance.	F	
45	BeamRdyToPick		0/1						39.76-73.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	45

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	UnlddTrckLeavs		0/1						39.76-73.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	45
	PlcBmToGround		0/1						39.76-73.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	45
	FnshPlcGrnd		0/1						39.76-73.76	This activity started one of its instances once. Also, no instances are taking place at SimTime.	F	45
	Preparation	0	0/0				√	Crew2Ready	39.76-73.76	The Combi in the blue colour means that it is now ready to start its instance. In addition, the thickness of the feeding link between the Combi and Queue changed which shows that the Combi is drawing its required resources.	F	45

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
46	BeamRdyToPick		0/1						39.76-73.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	46
	UnlddTrckLeavs		0/1						39.76-73.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	46
	PlcBmToGround		0/1						39.76-73.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	46
	FnshPlcGrnd		0/1						39.76-73.76	This activity started one of its instances once. Also, no instances are taking place at SimTime.	F	46

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	Preparation	0	0/0				√	Crew1Ready	39.76-73.76	The Combi in the blue colour means that it is now ready to start its instance. In addition, the thickness of the feeding link between the Combi and Queue changed which shows the Combi is drawing its required resources.	F	46
47	BeamRdyToPick		0/1						39.76-73.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	47
	UnlddTrckLeavs		0/1						39.76-73.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	47
	PlcBmToGround		0/1						39.76-73.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	47

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	FnshPlcGrnd		0/1						39.76-73.76	This activity started one of its instances once. Also, no instances are taking place at SimTime.	F	47
	Preparation	0	0/0				√	Crew3Ready	39.76-73.76	The Combi in the blue colour means that it is now ready to start its instance. In addition, the thickness of the feeding link between the Combi and Queue changed which shows the Combi is drawing its required resources.	F	47
48	BeamRdyToPick		0/1						39.76-73.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	48
	UnlddTrckLeavs		0/1						39.76-73.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	48

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	PlcBmToGr ound		0/1						39.76-73.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	48
	FnshPlcGrn d		0/1						39.76-73.76	This activity started one of its instances once. Also, no instances are taking place at SimTime.	F	48
	Preparation		1/1						39.76-73.76	The change of colour of the border of this Combi shows that it has completed its instance. Also, the numbers on the top of the activity show that this Combi started one of its instances once since the model execution began.	F	48
49	BeamRdyToPick		0/1						39.76-73.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instances, and is ready to release its resources into the associated Queues.	F	49

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	UnlddTrckLeavs		0/1						39.76-73.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	49
	PlcBmToGround		0/1						39.76-73.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	49
	FnshPlcGrnd		0/1						39.76-73.76	This activity started one of its instances once. Also, no instances are taking place at SimTime.	F	49
	Preparation		1/1	0					39.76-73.76	The red colour of the Combi's border shows that the Combi is ready to terminate its instance.	F	49

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
50	BeamRdyToPick		0/1						39.76-73.76	The Combi started one of its instances and, at the current time, no instance is taking place. The changes of the thickness of the released link between Combi and Queue show that Combi terminates one of its instanced, and is ready to release its resources into the associated Queues.	F	50
	UnlddTrckLeavs		0/1						39.76-73.76	The colour of the border changed which shows that the Activity has already terminated its instance.	F	50
	PlcBmToGround		0/1						39.76-73.76	By SimTime, this Combi has started one of its instances, and at SimTime, no instance of this activity is taking place.	F	50
	FnshPlcGrnd		0/1						39.76-73.76	This activity started one of its instances once. Also, no instances are taking place at SimTime.	F	50

State	Combi/Normal	Number			Other changes				SimTime	Description of the state	System description according to the state	Figure number
		Top Left	Middle	Top Right	Link between Combi and Normal (Start of Normal is depending on the finish of Combi)	Thickness of Released Link from Combi/ Normal to Queue, or between Combi and Normal activity is changed	Thickness of Feeding link from Queue to Combi is changed	The Queue involved in feeding or releasing, and resource allocating				
	Preparation		1/1	0					39.76-73.76	The red colour of the Combi's border shows that the Combi is ready to terminate its instance.	F	50
	FinishPrpratn	0	0/0						39.76-73.76	The termination of the instance of the Preparation Combi leads to starting the instance of the next activity.	F	50

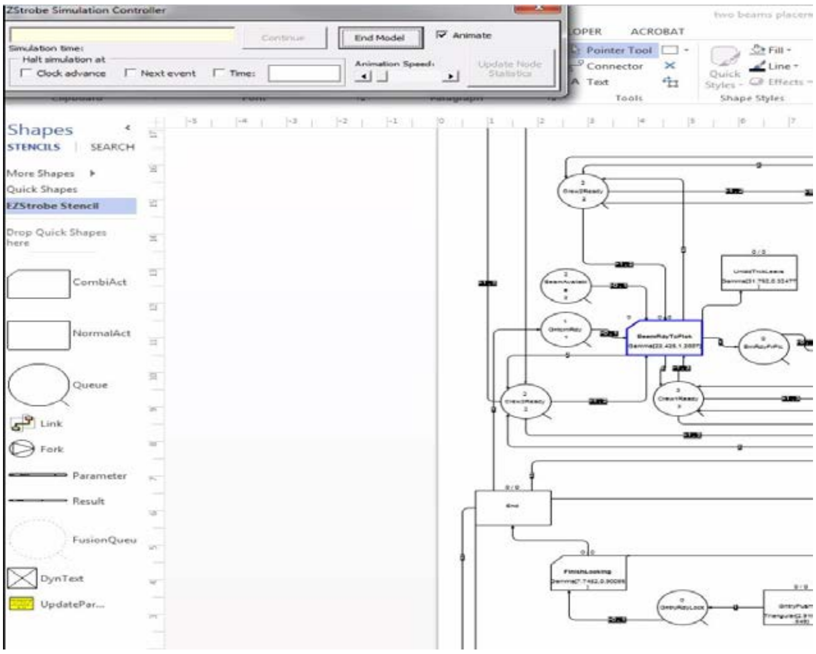

Figure A1 System State 1

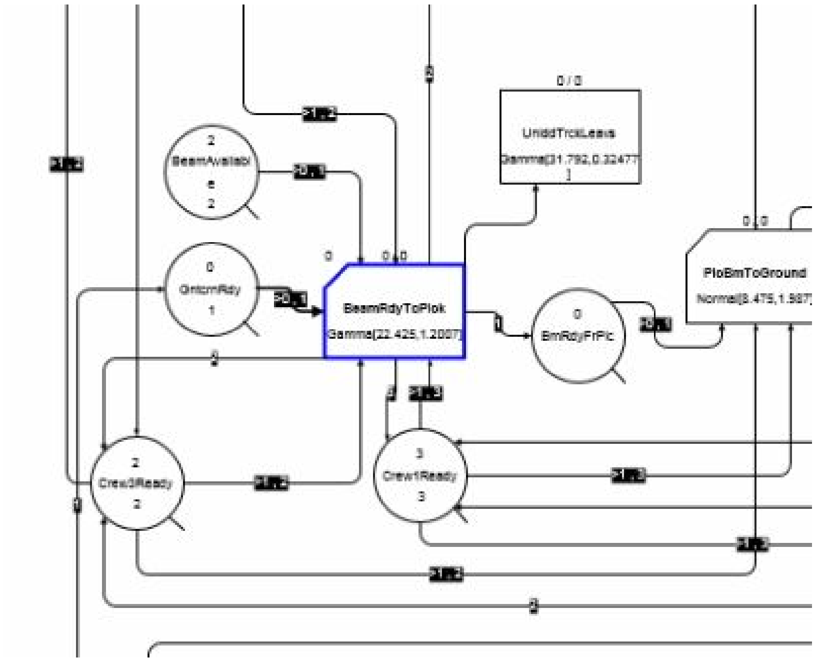

Figure A2 System State 2

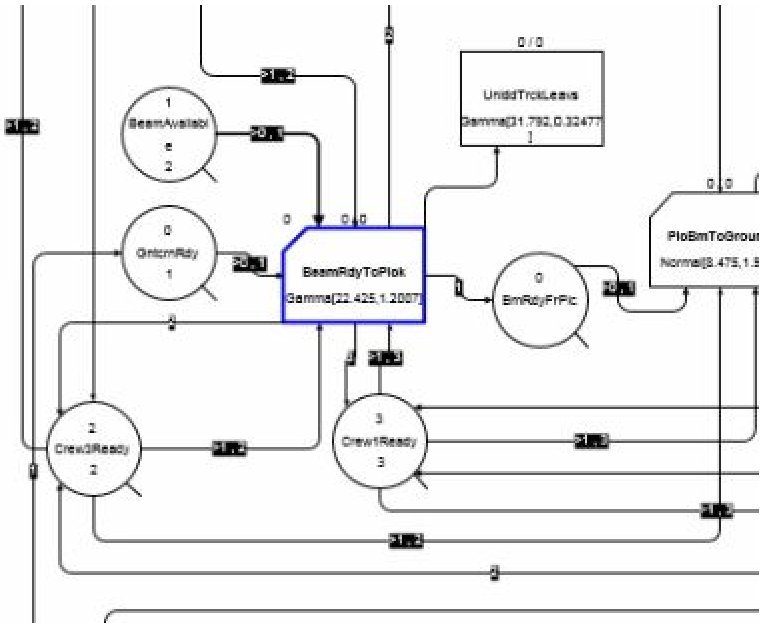

Figure A3 System State 3

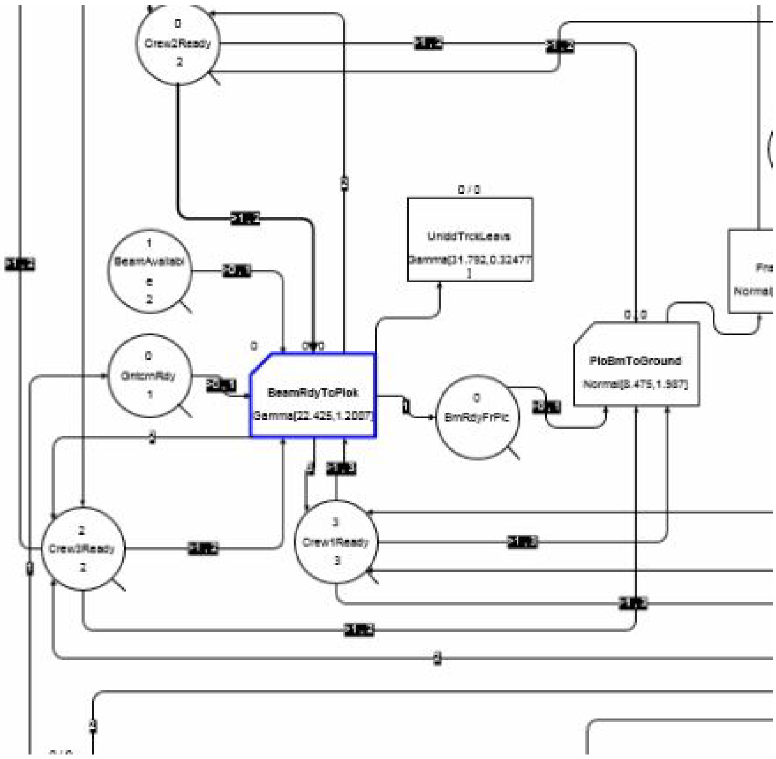

Figure A4 System State 4

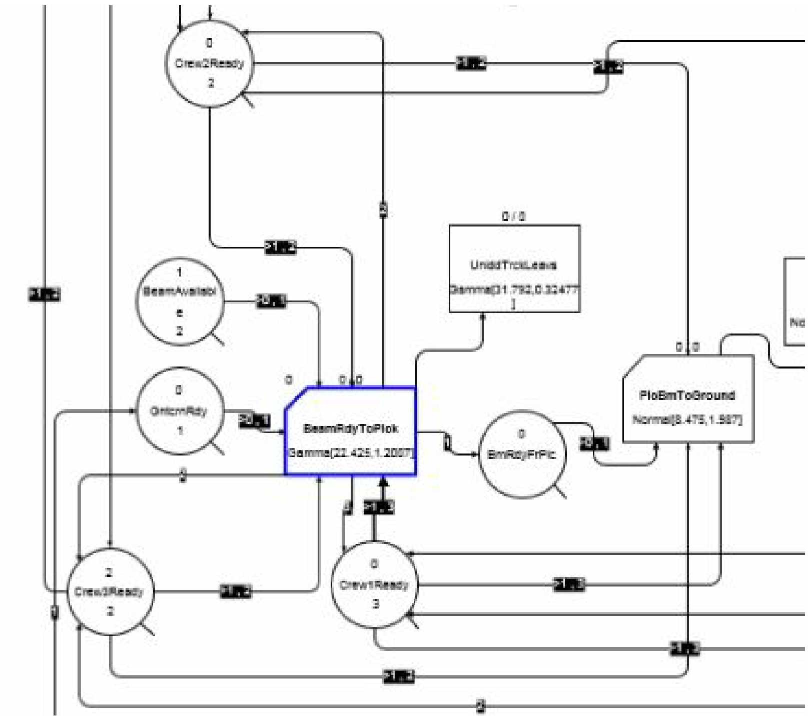

Figure A5 System State 5

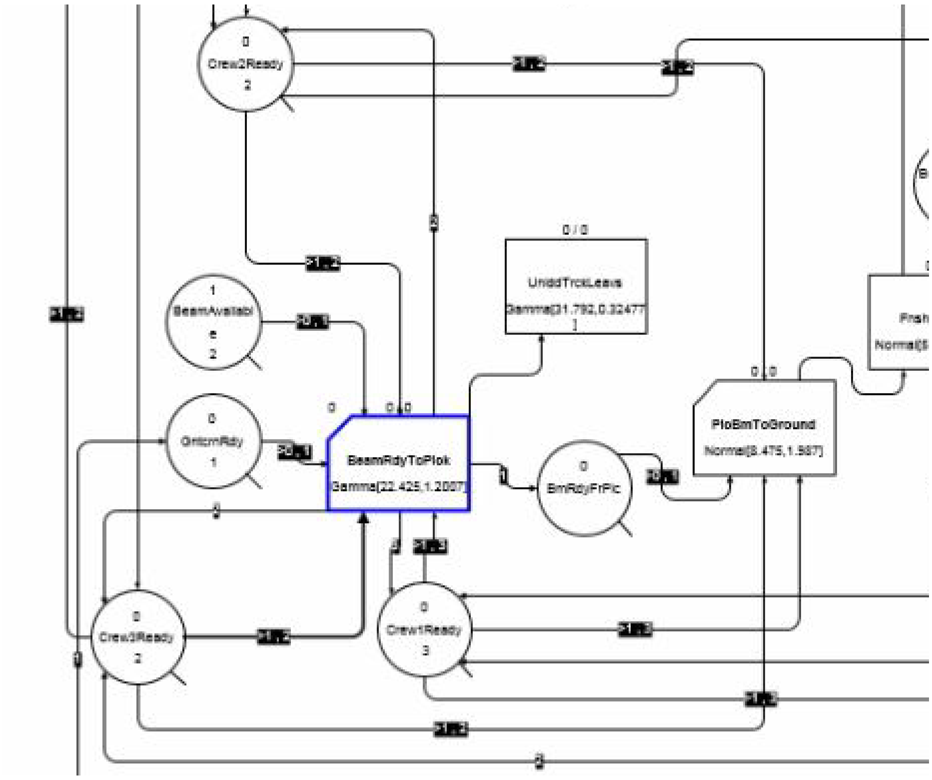

Figure A6 System State 6

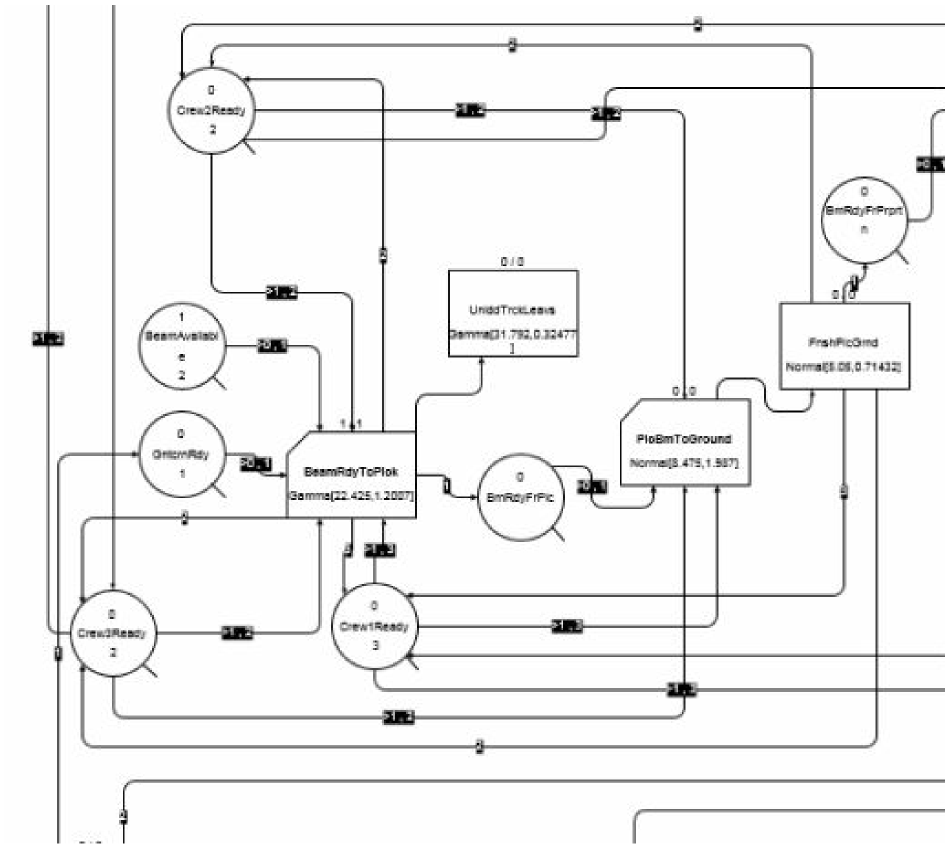

Figure A7 System State 7

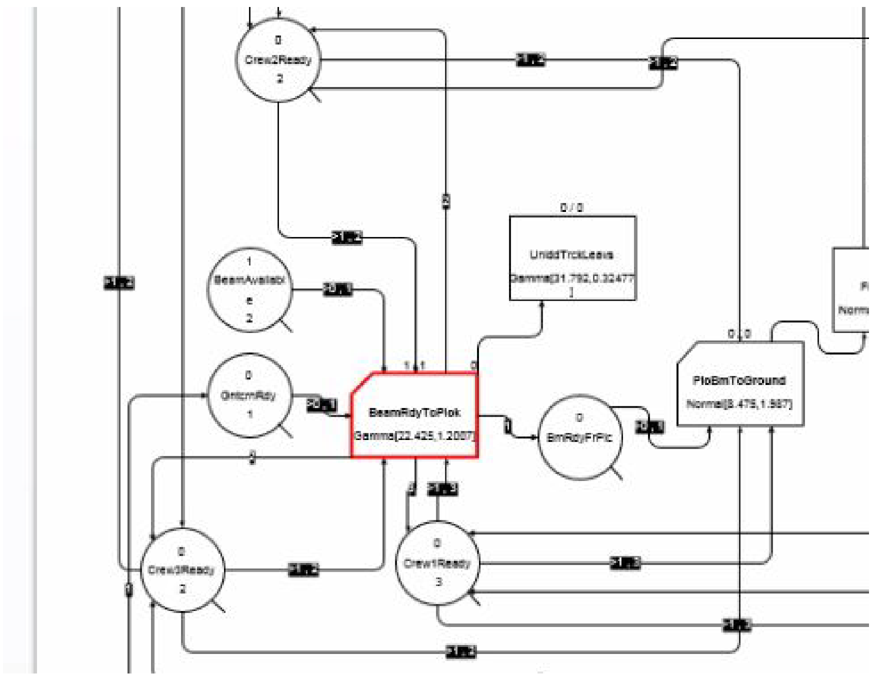

Figure A8 System State 8

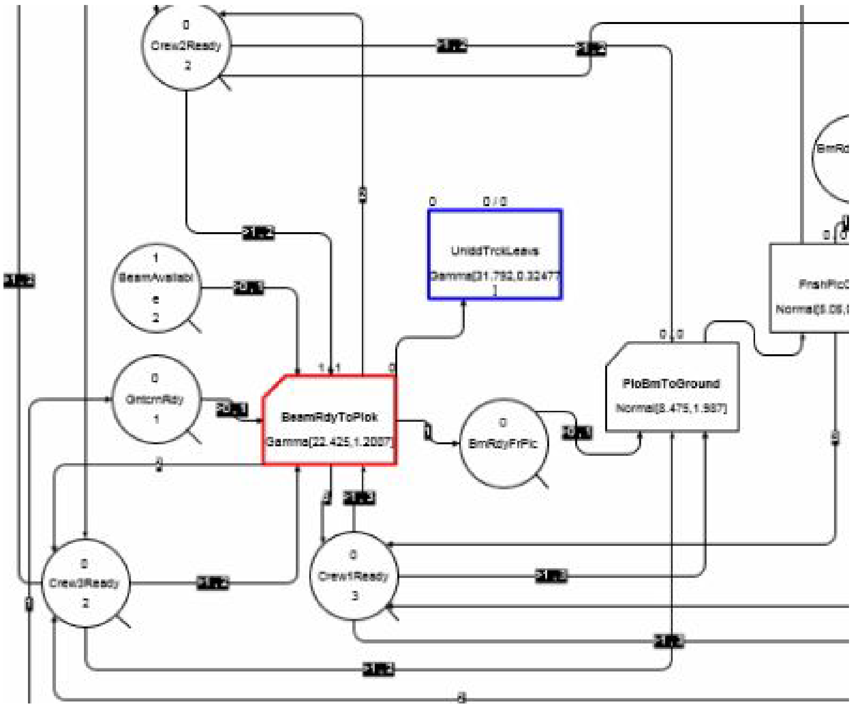

Figure A9 System State 9

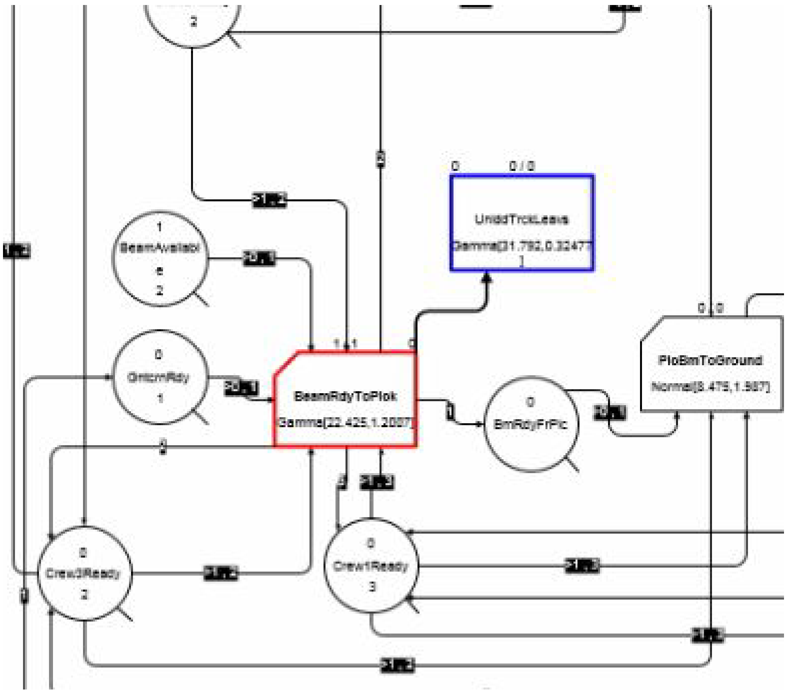

Figure A10 System State 10

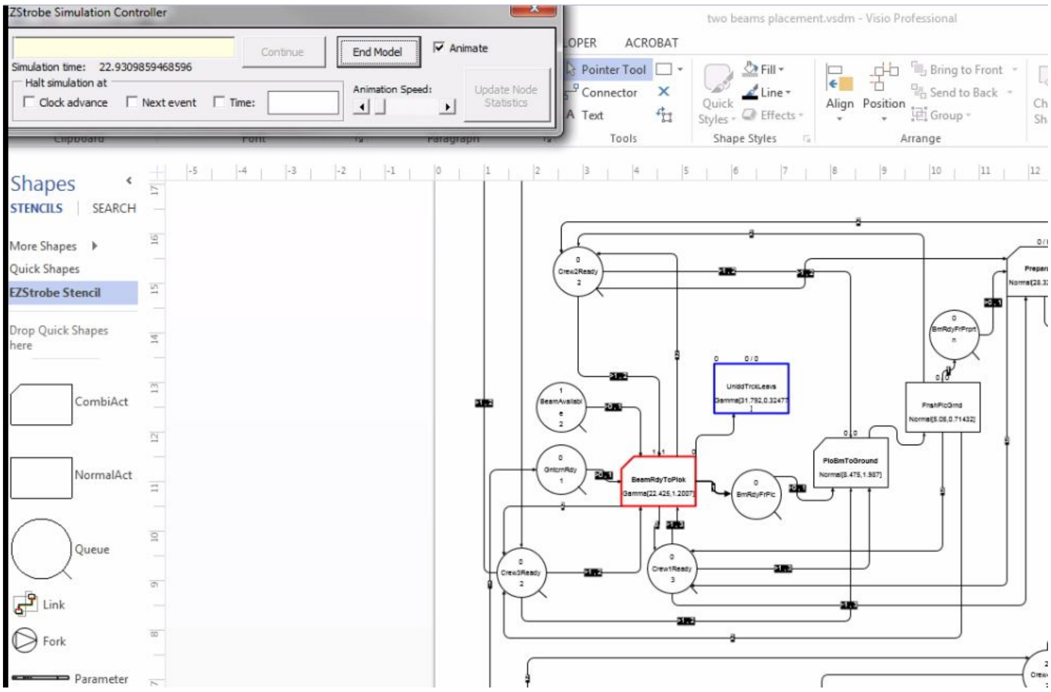

Figure A11 System State 11

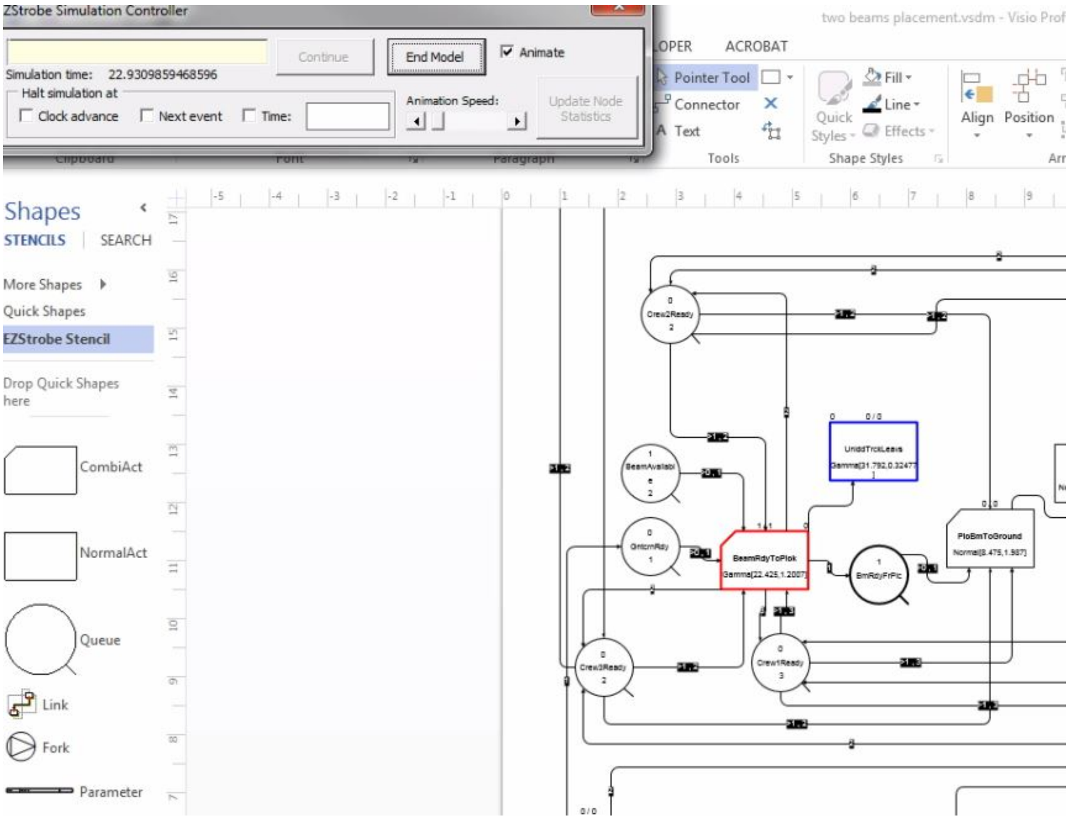

Figure A12 System State 12

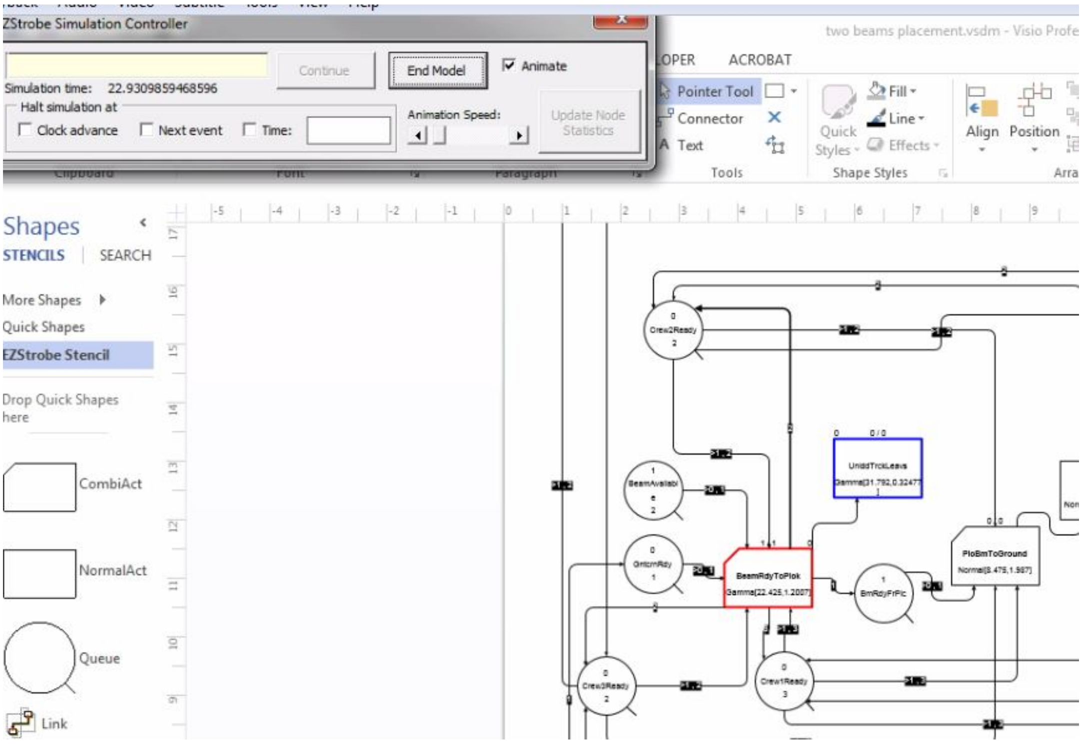

Figure A13 System State 13

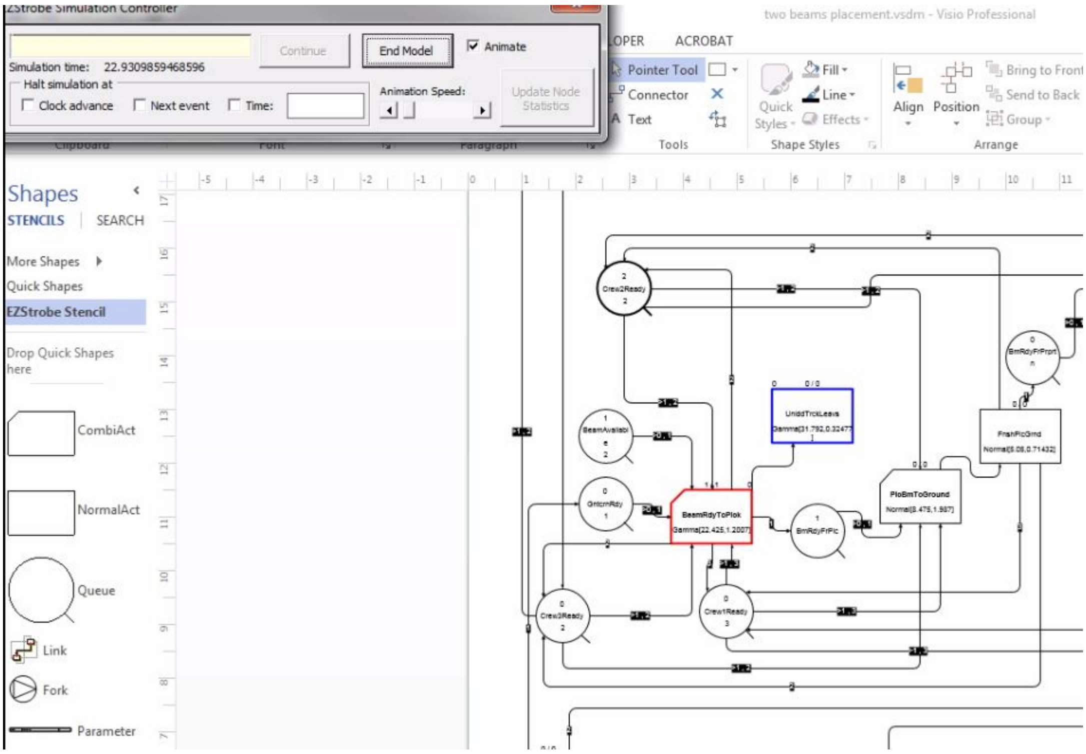

Figure A14 System State 14

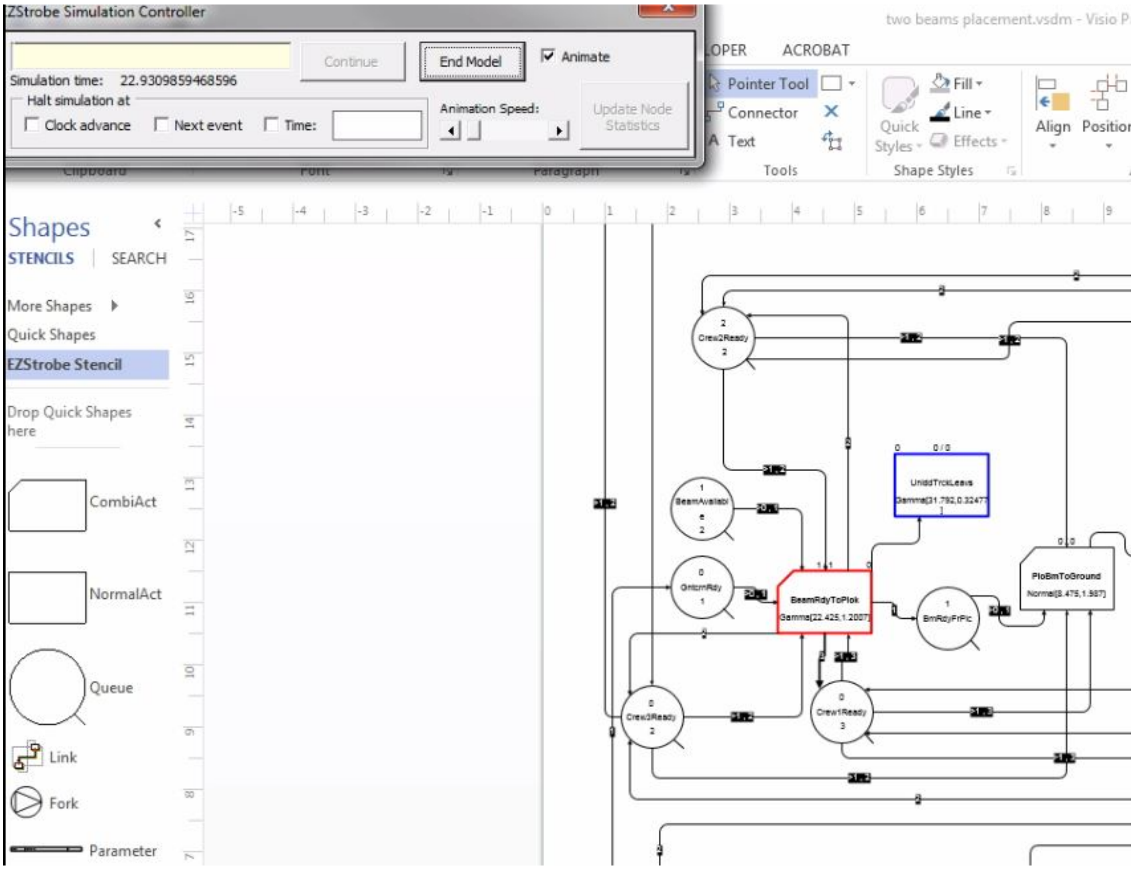

Figure A15 System State 15

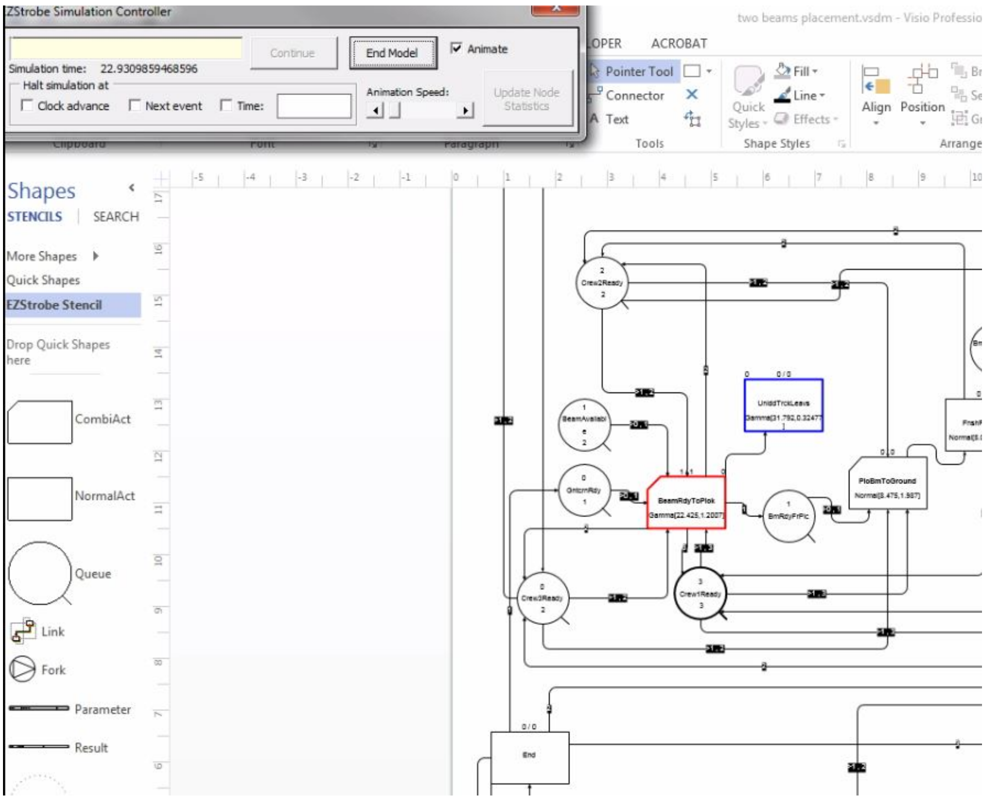

Figure A16 System State 16

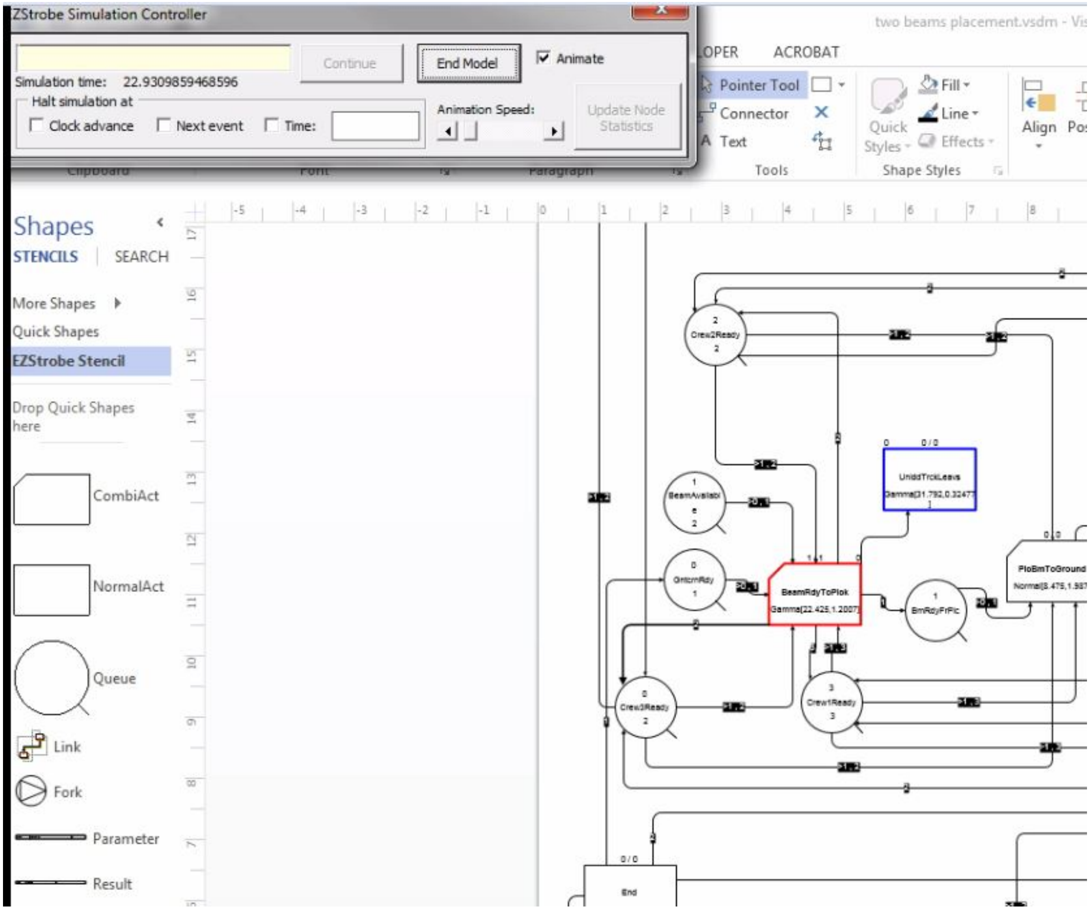

Figure A17 System State 17

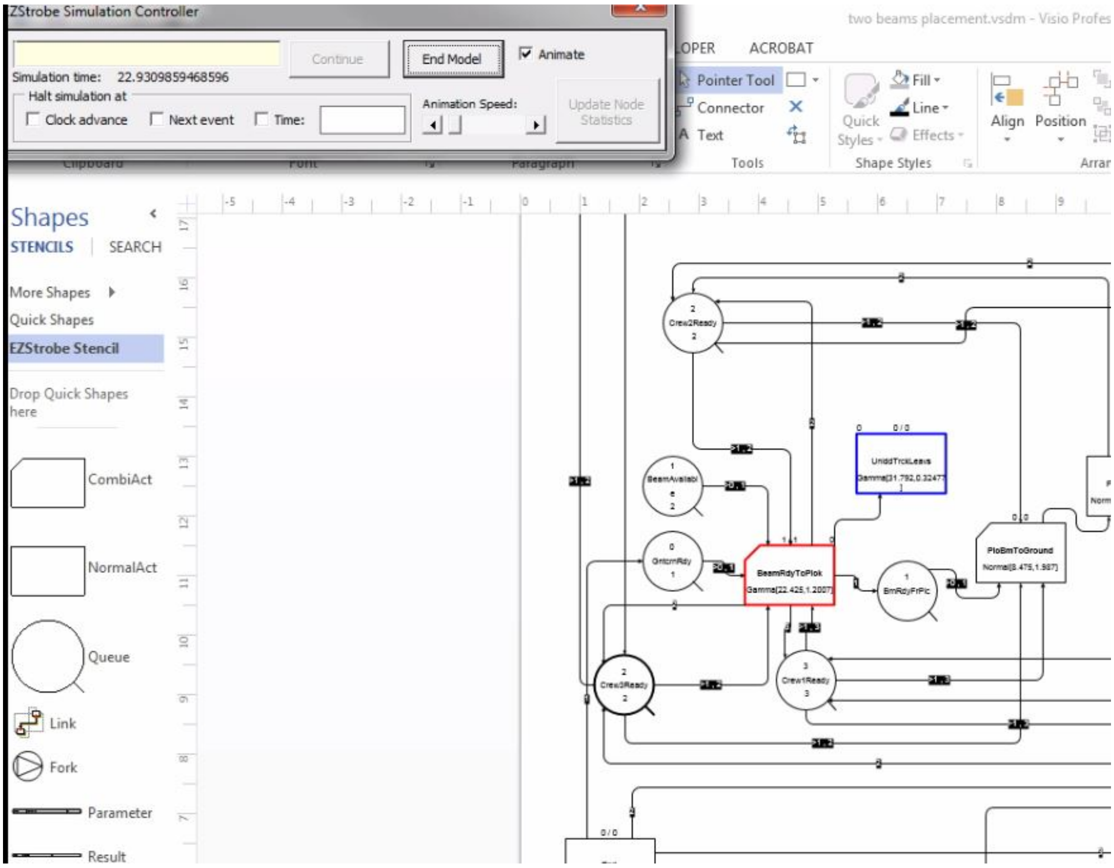

Figure A18 System State 18

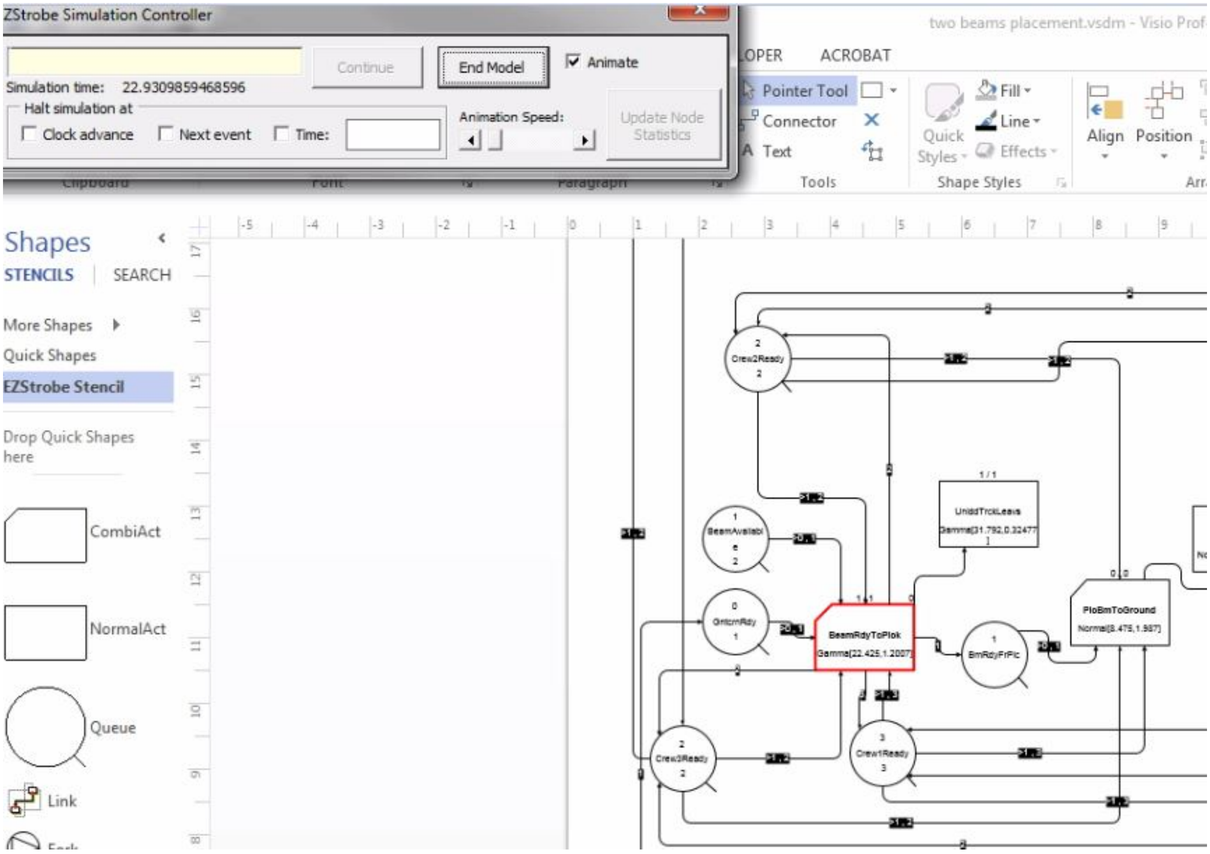

Figure A19 System State 19

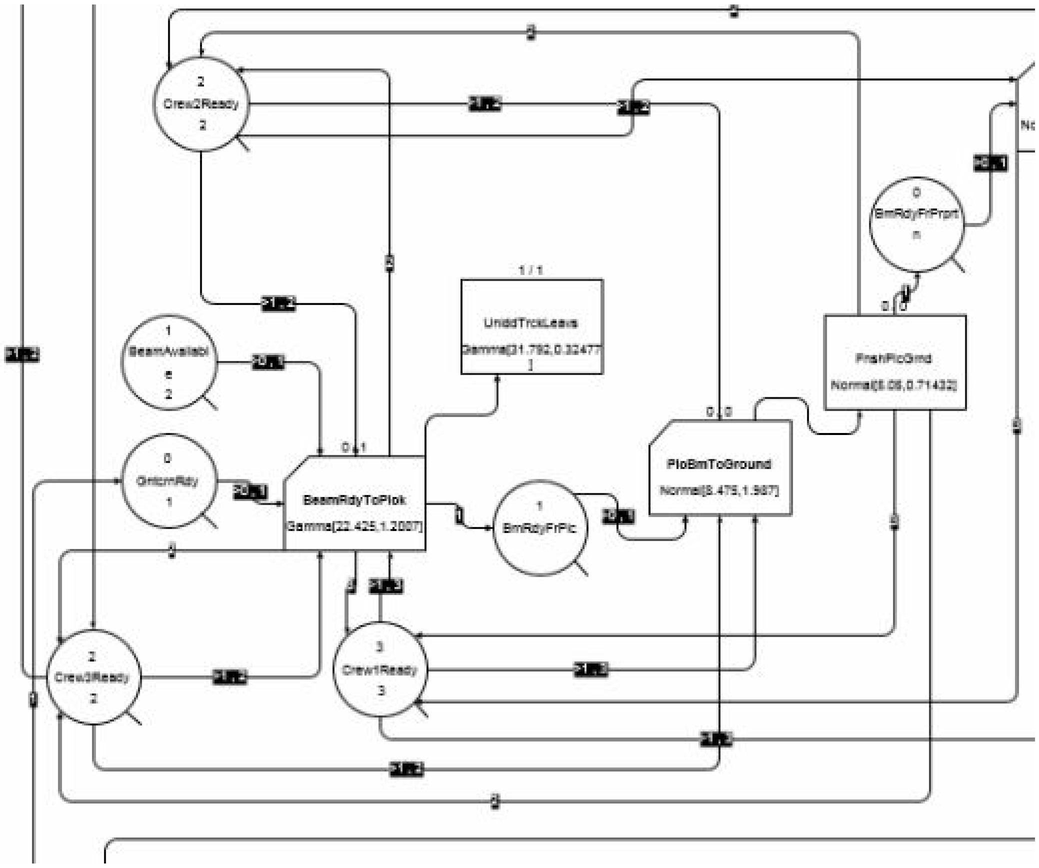

Figure A20 System State 20

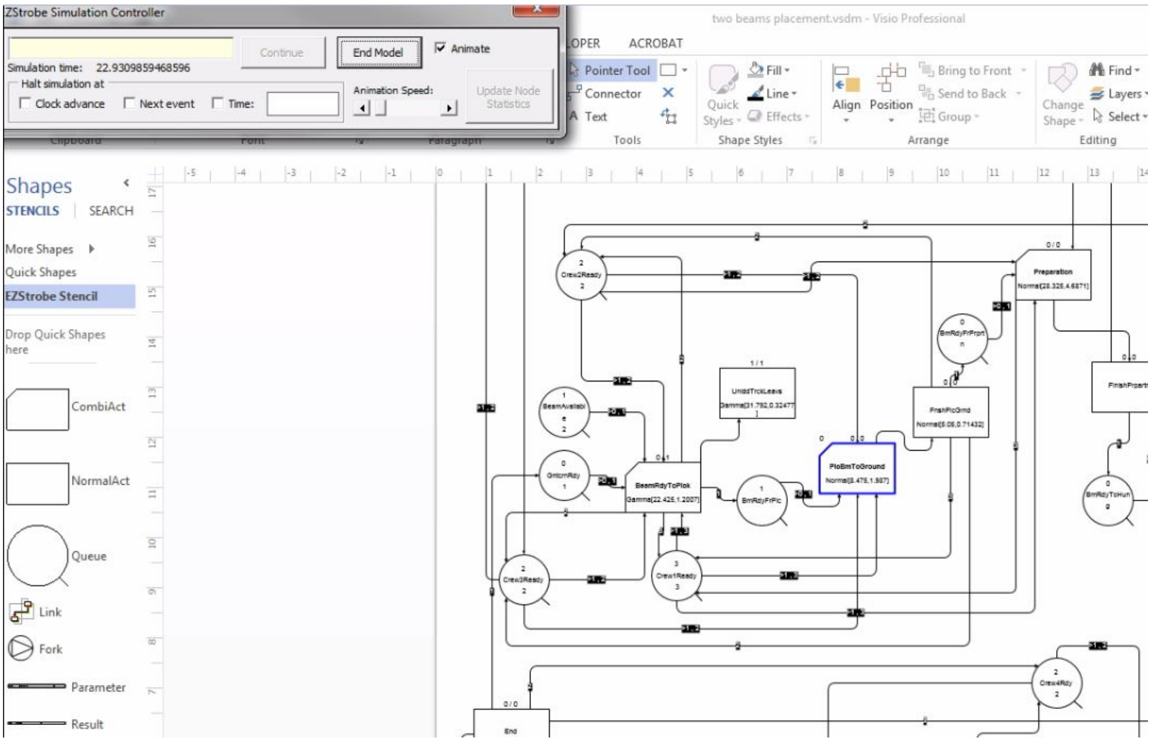

Figure A21 System State 21

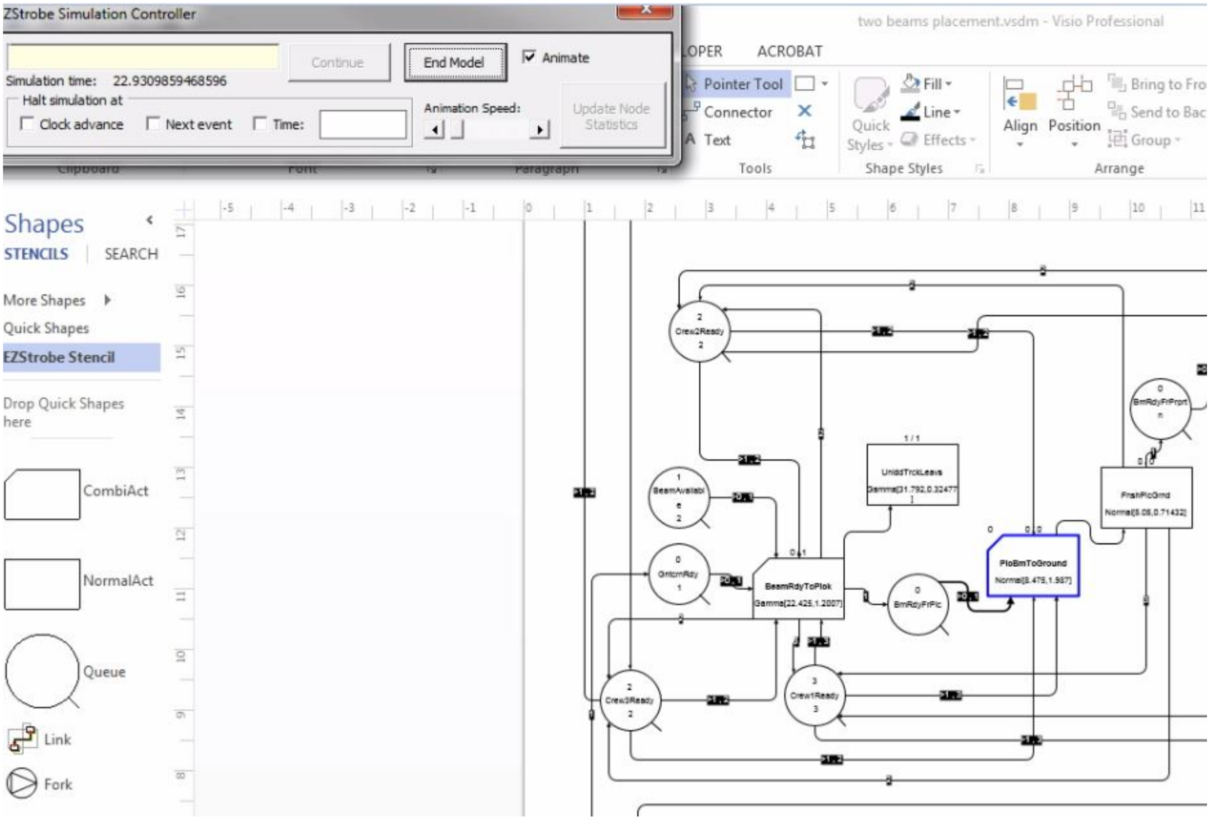

Figure A22 System State 22

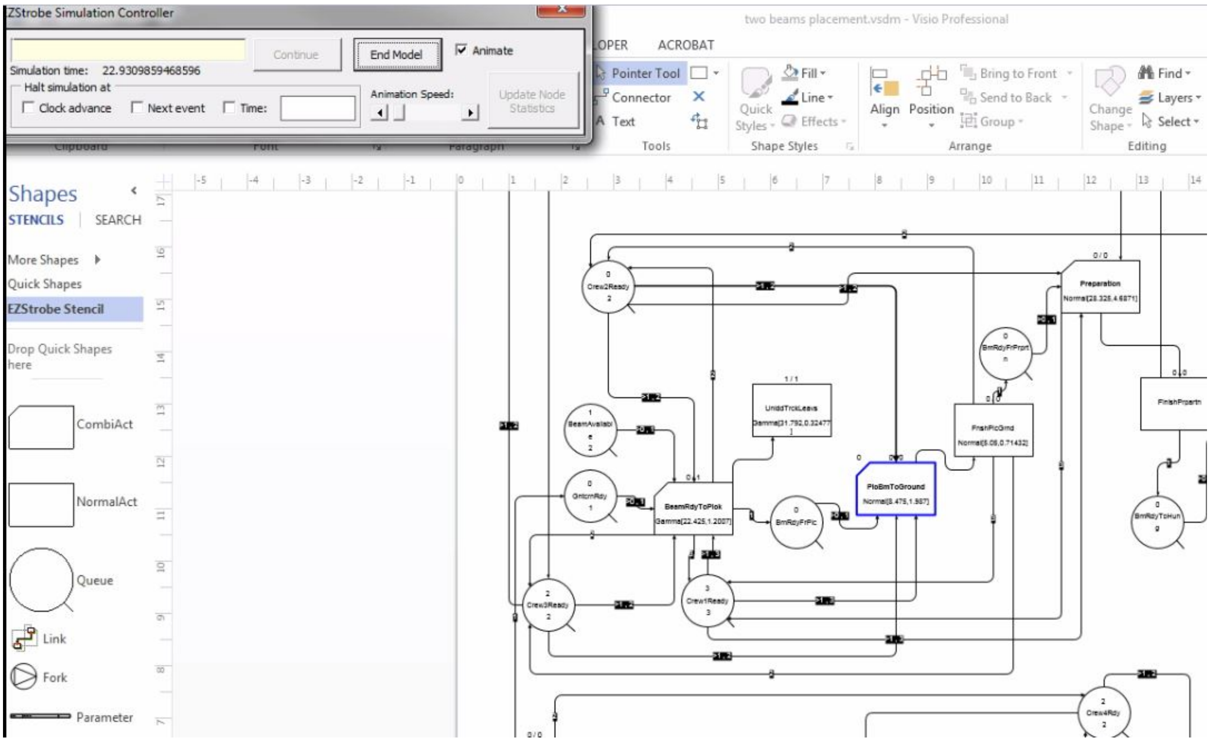

Figure A23 System State 23

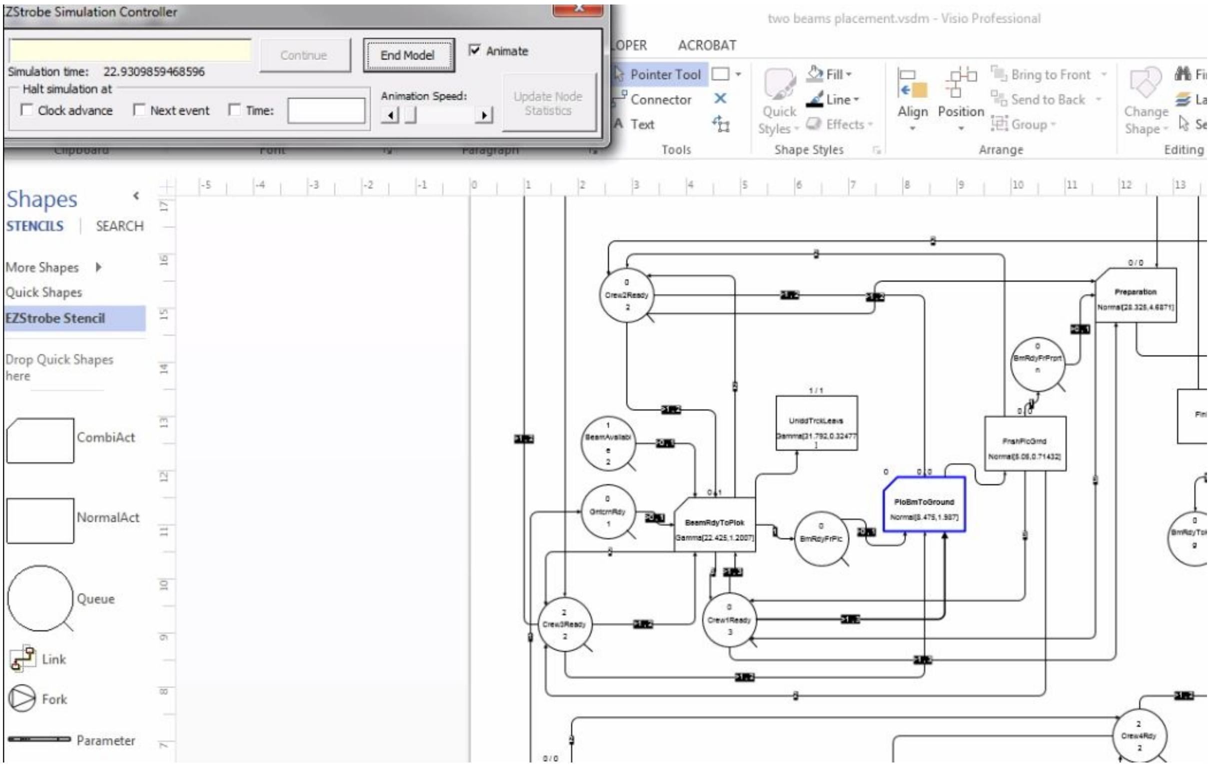

Figure A24 System State 24

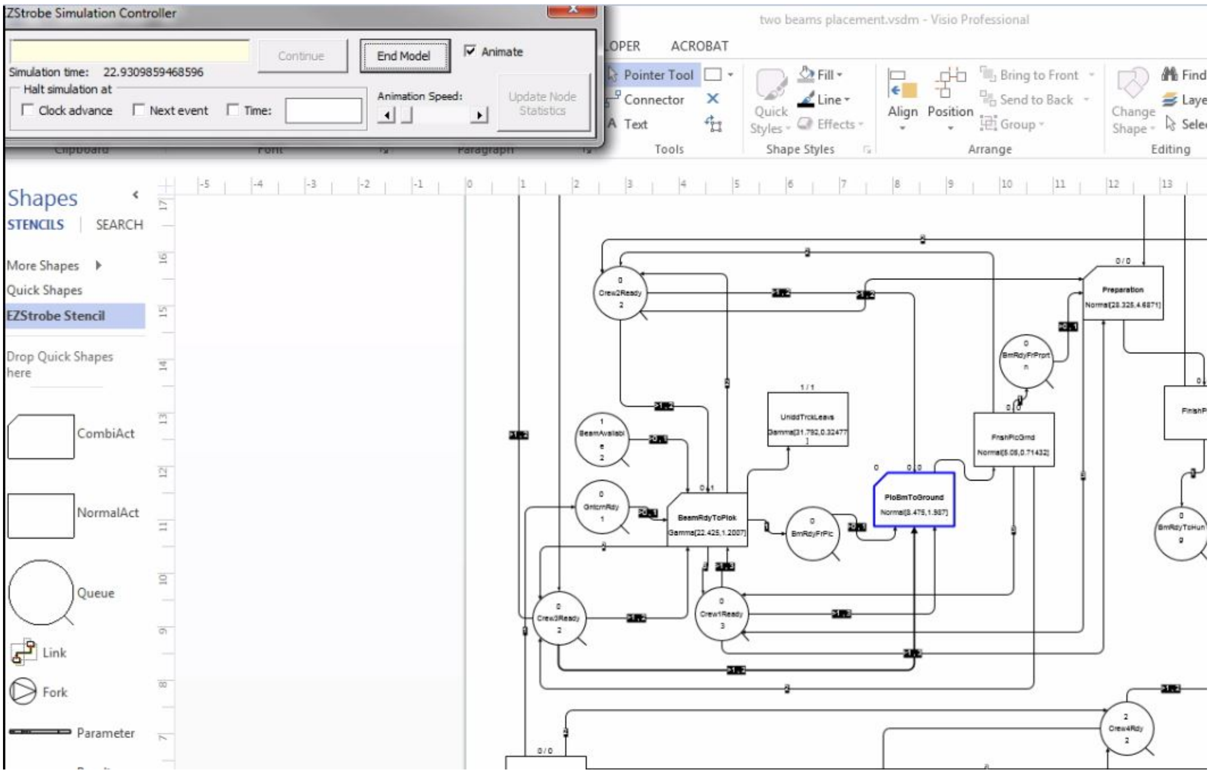

Figure A25 System State 25

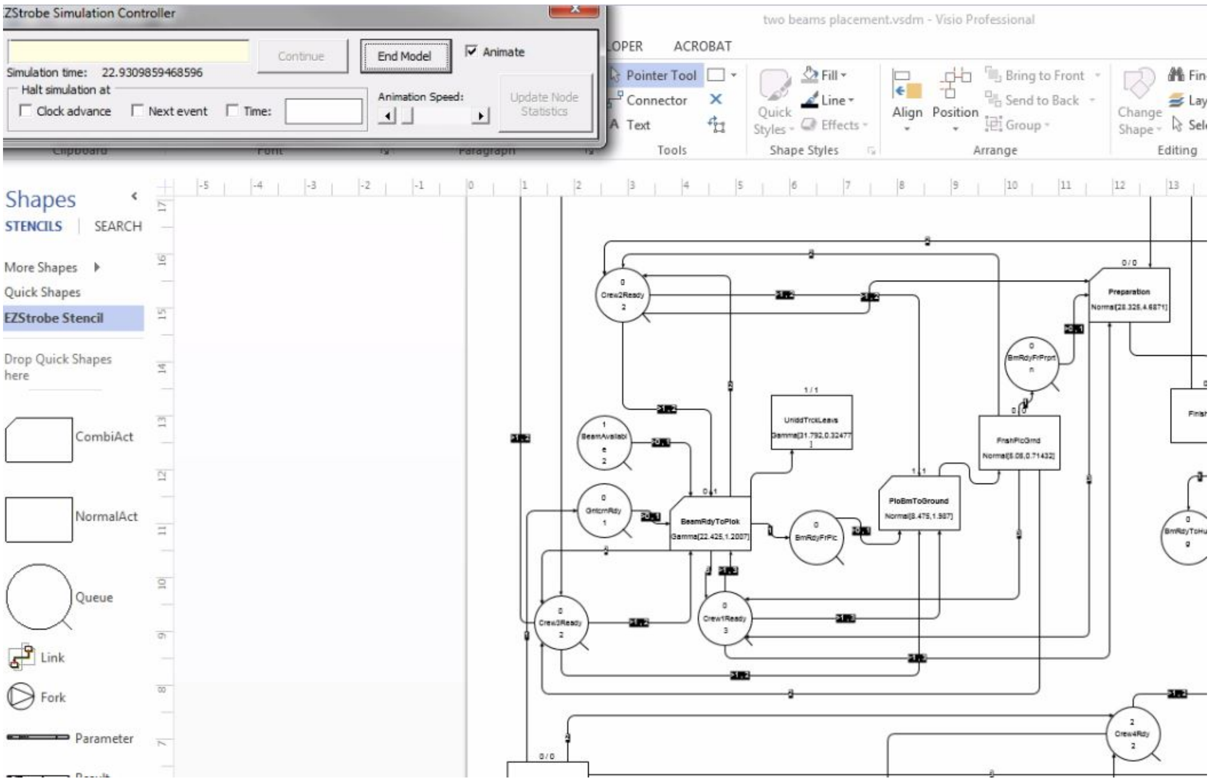

Figure A26 System State 26

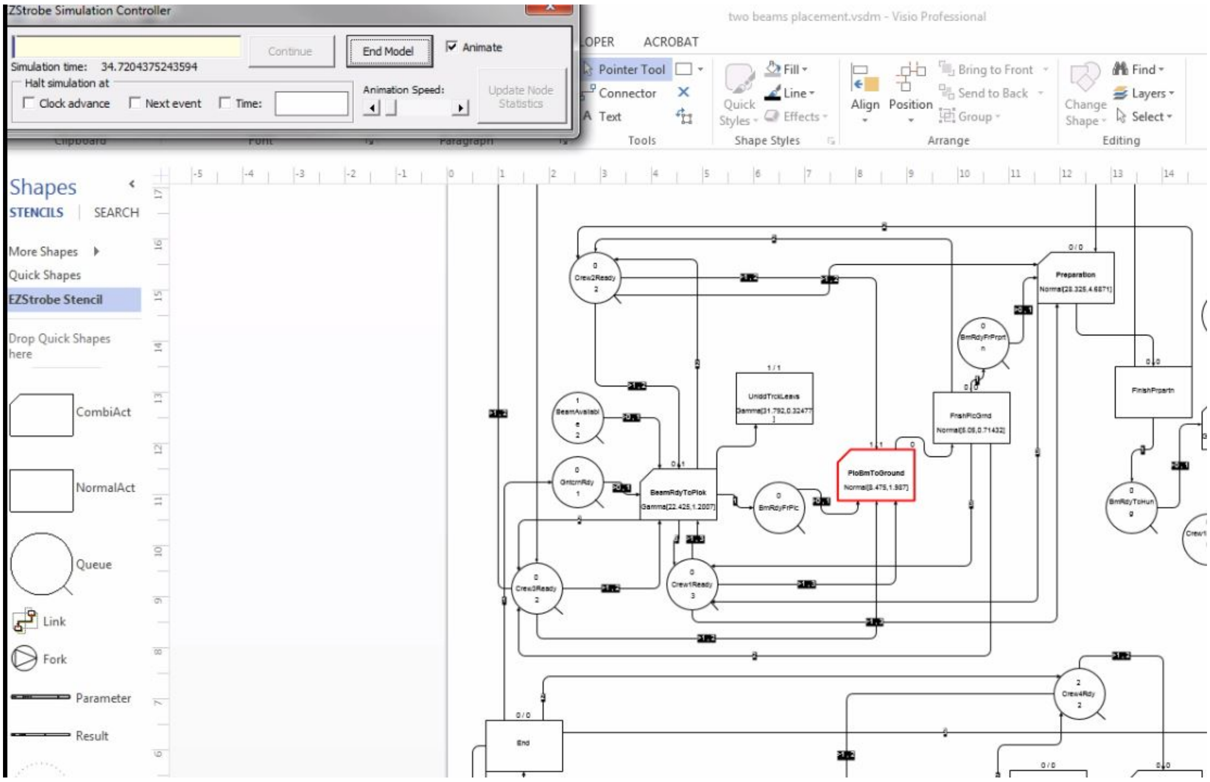

Figure A27 System State 27

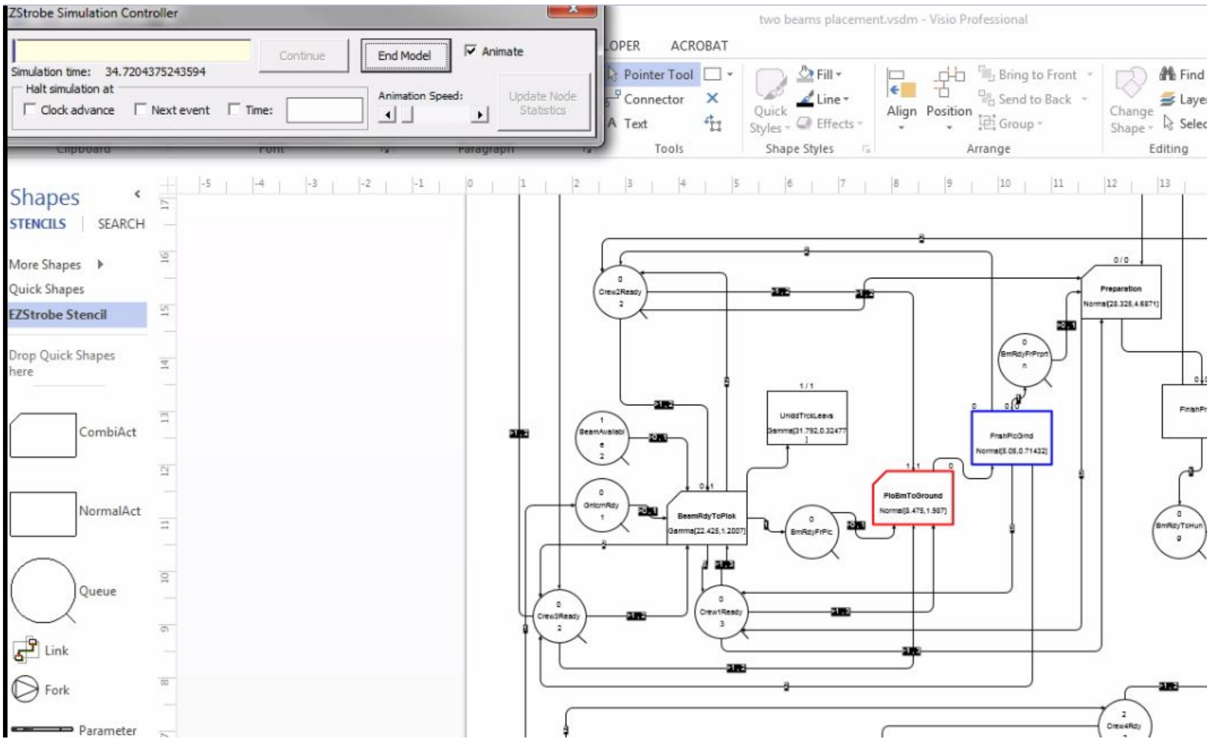

Figure A28 System State 28

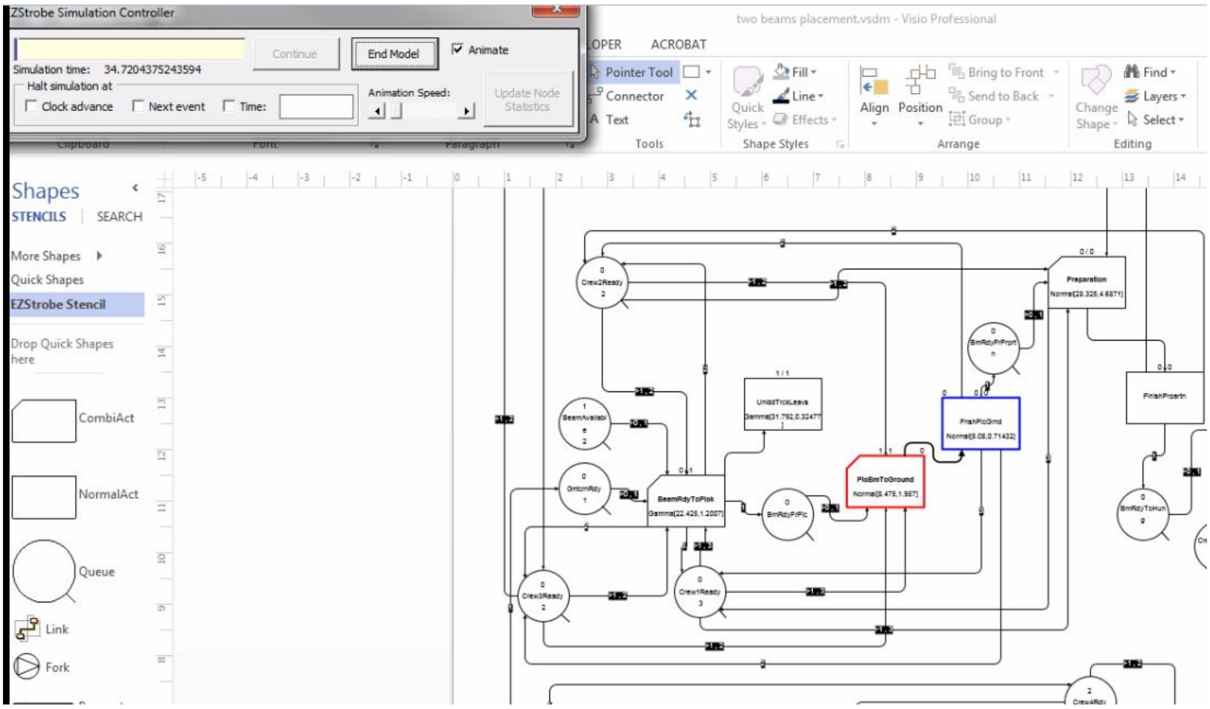

Figure A29 System State 29

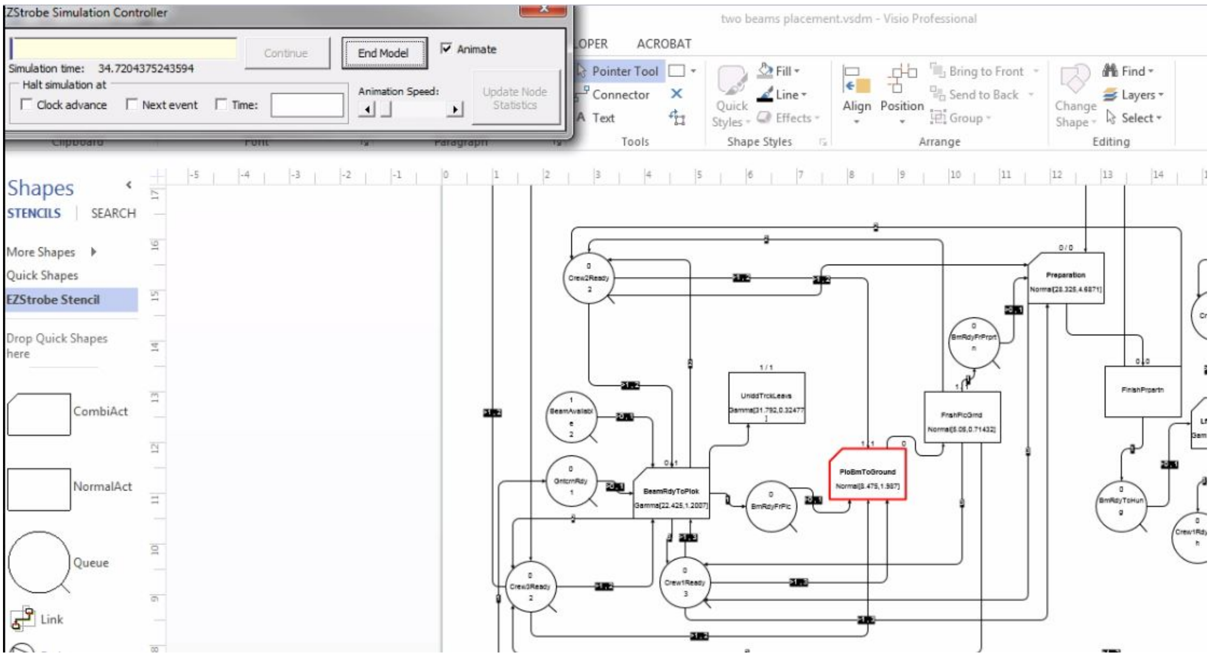

Figure A30 System State 30

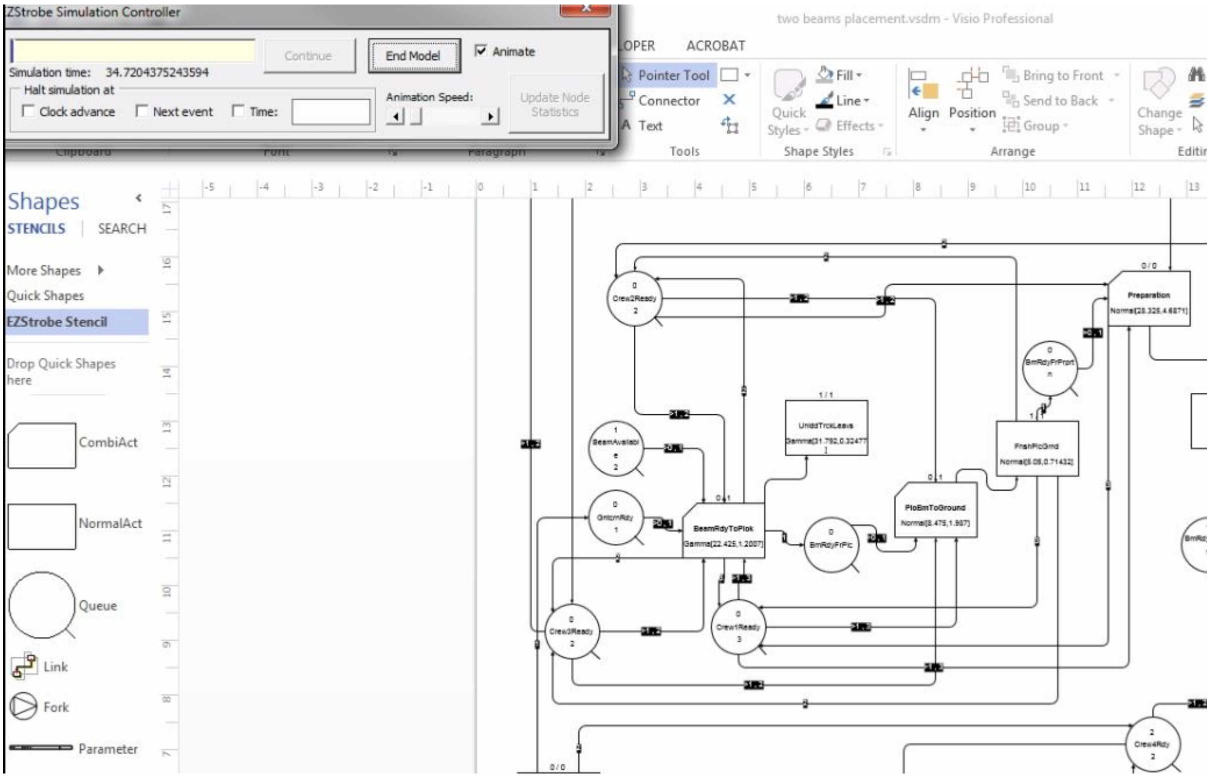

Figure A31 System State 31

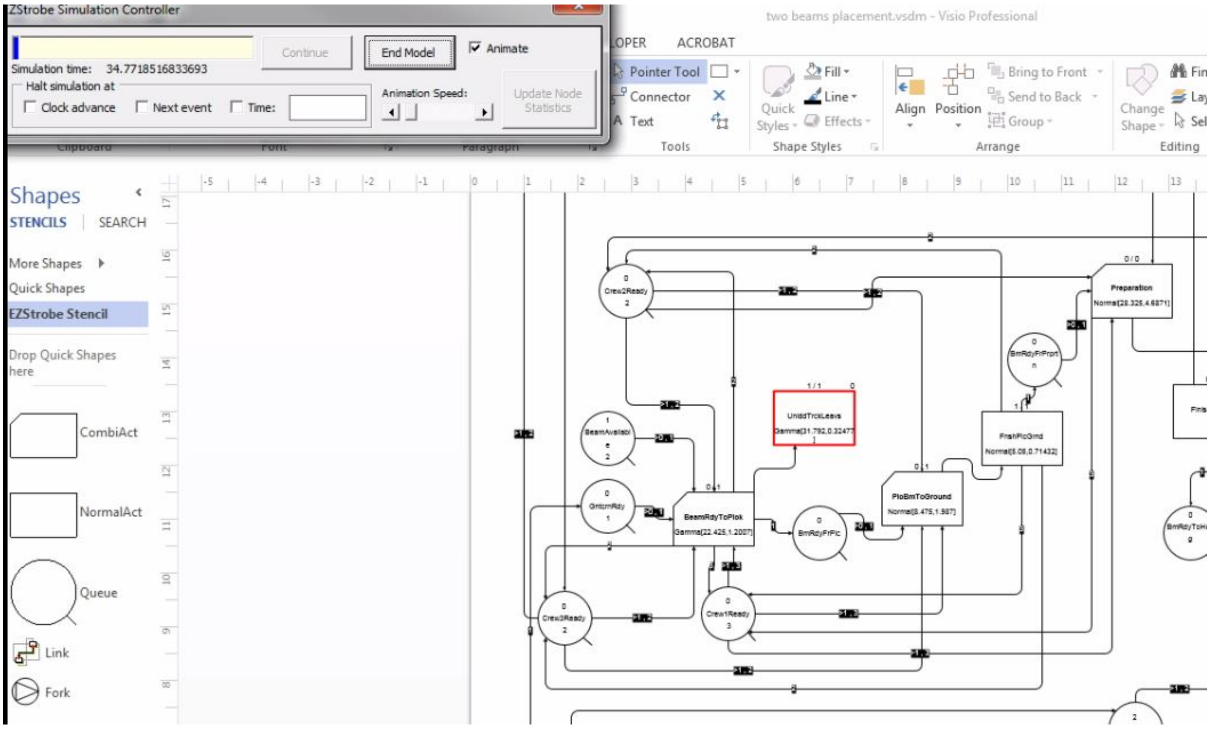

Figure A32 System State 32

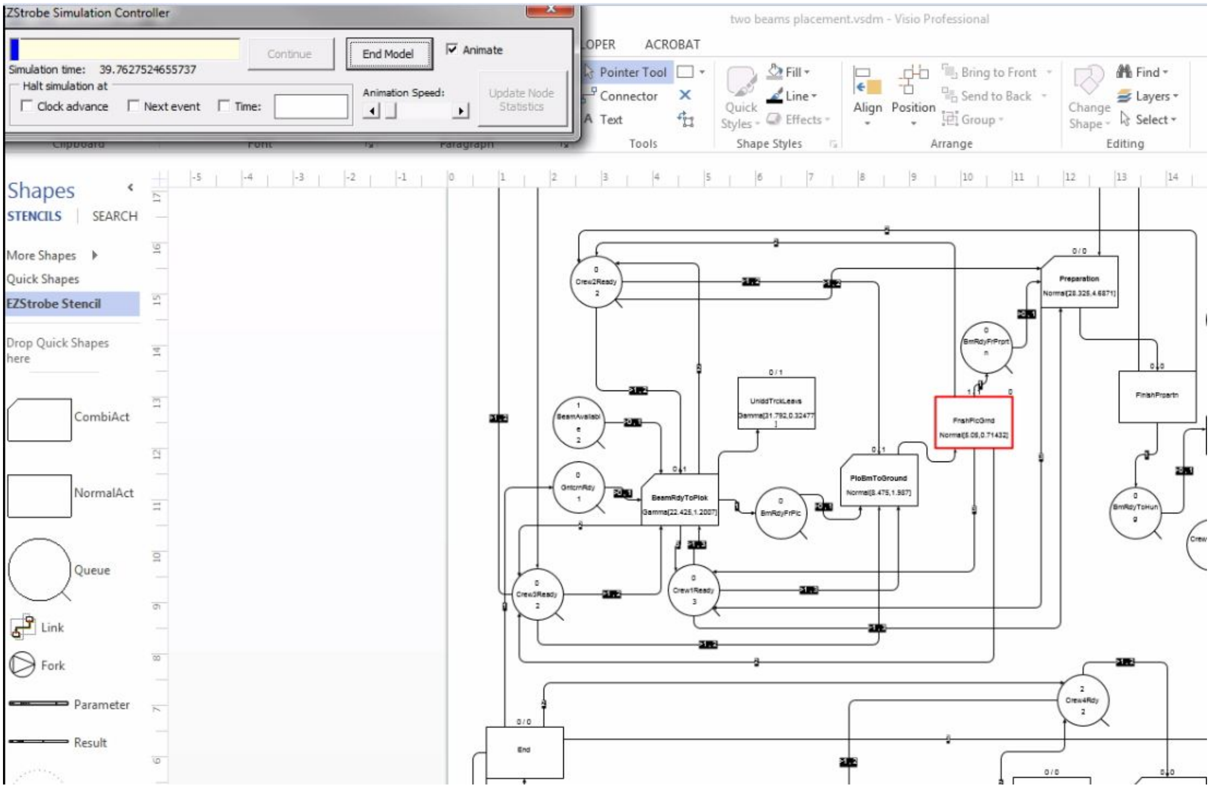

Figure A33 System State 33

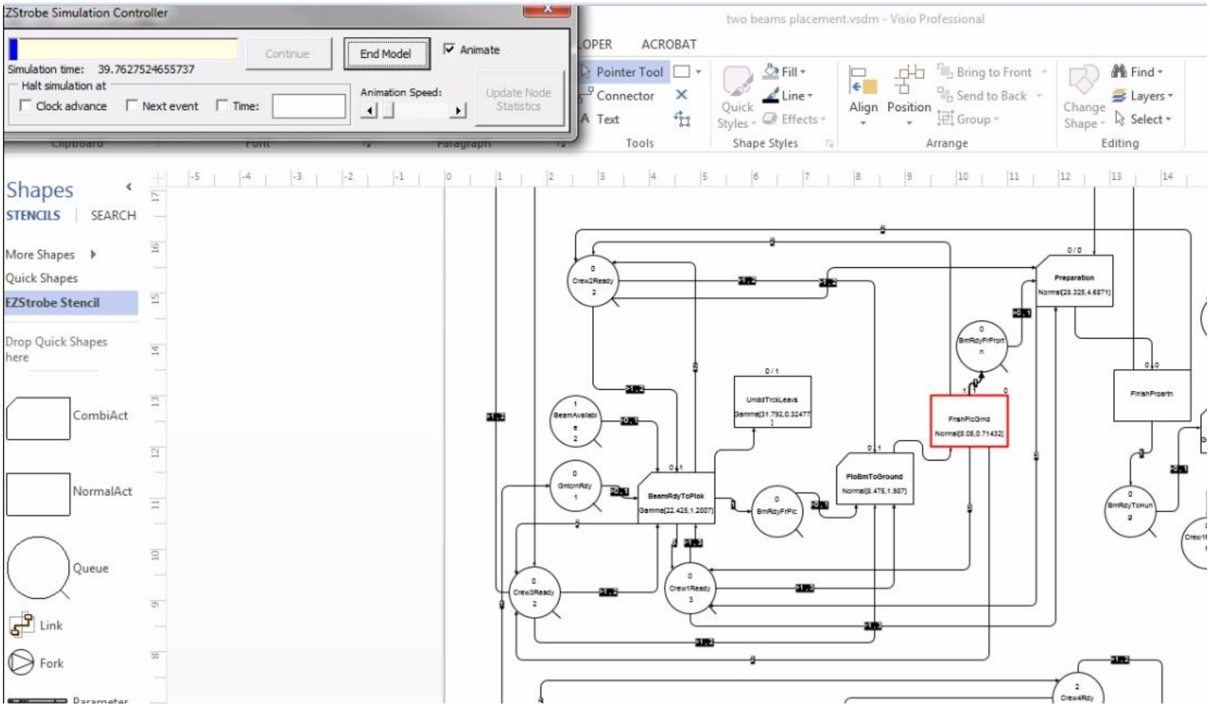

Figure A34 System State 34

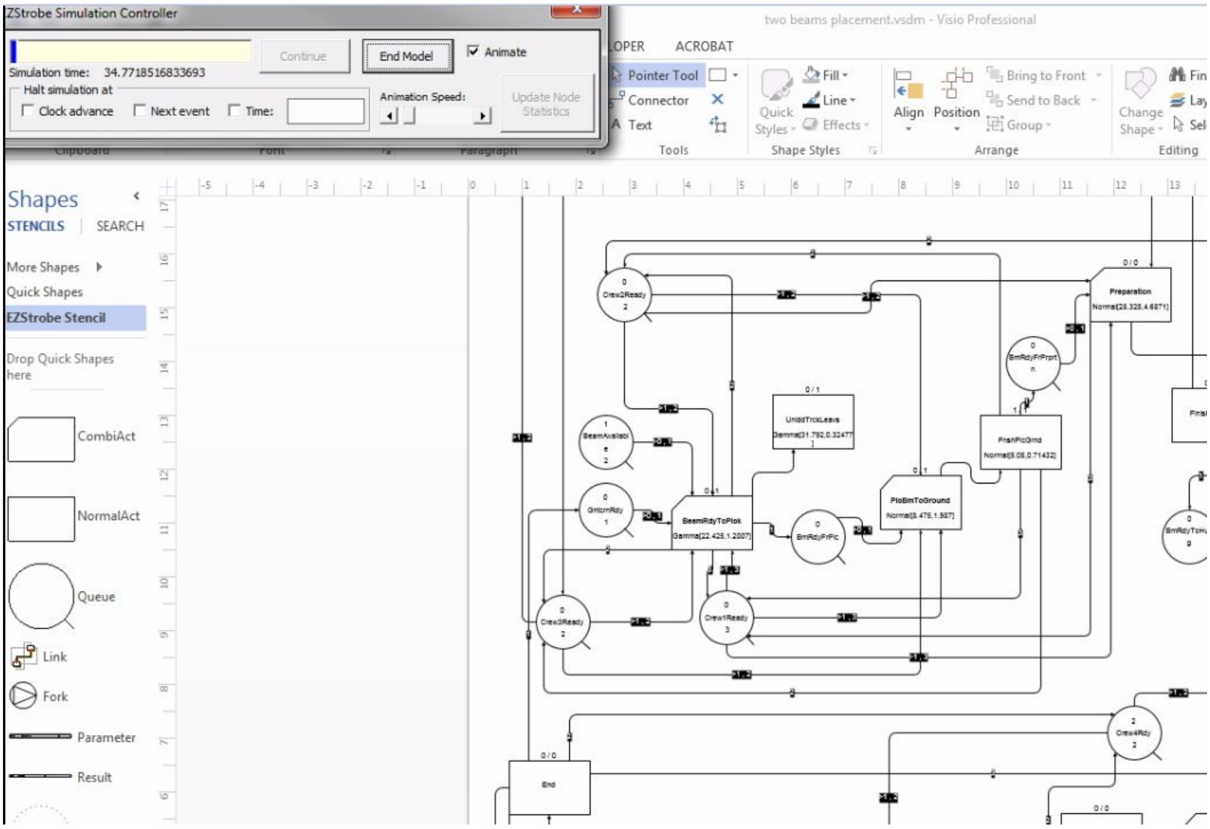

Figure A35 System State 35

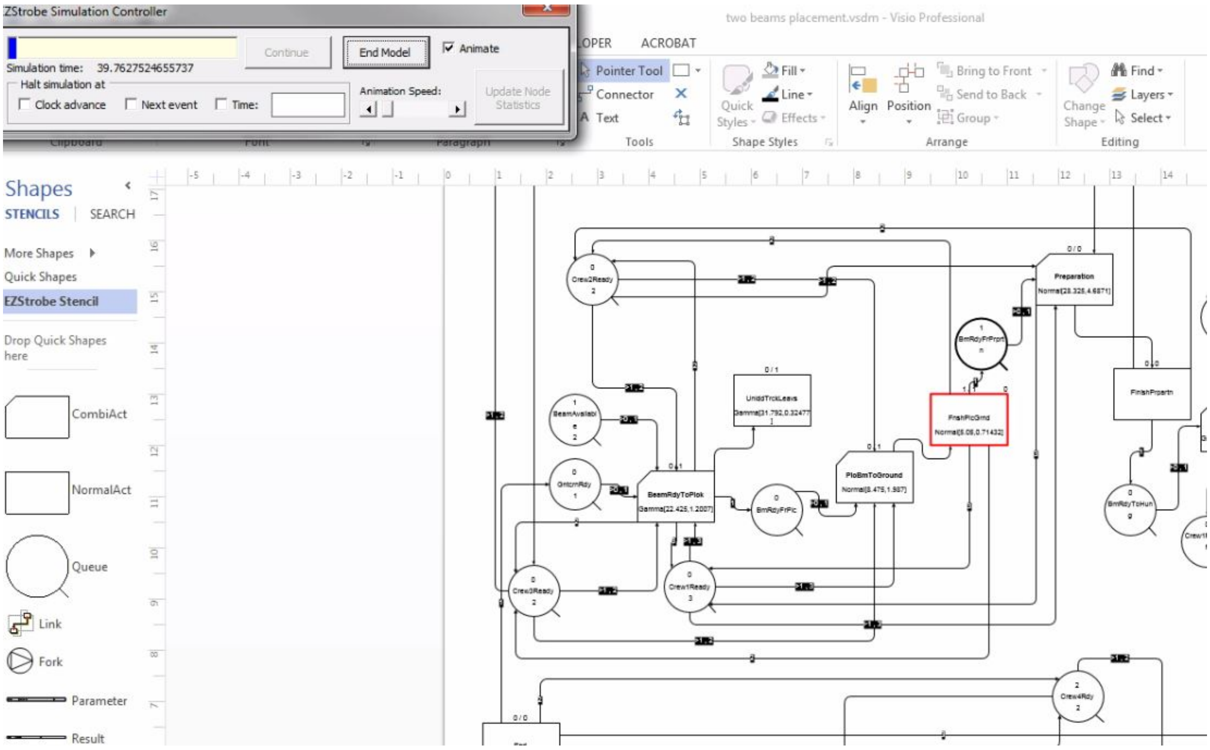

Figure A36 System State 36

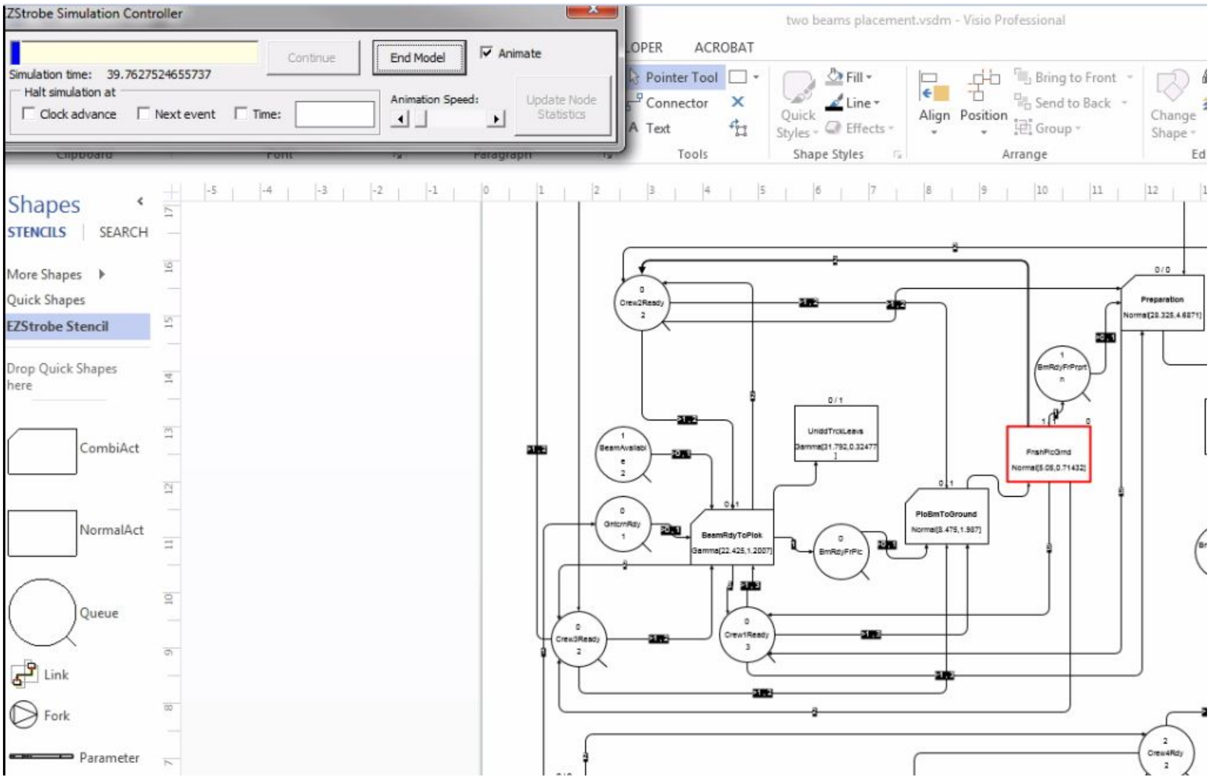

Figure A37 System State 37

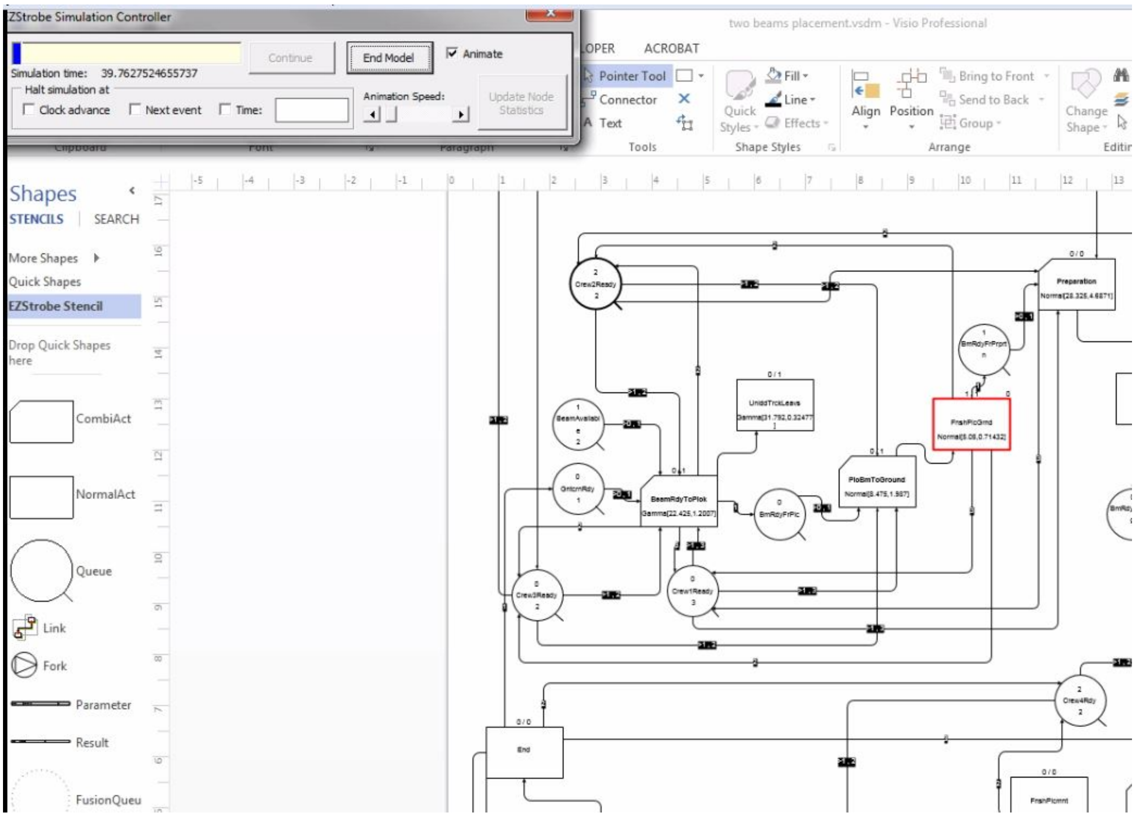

Figure A38 System State 38

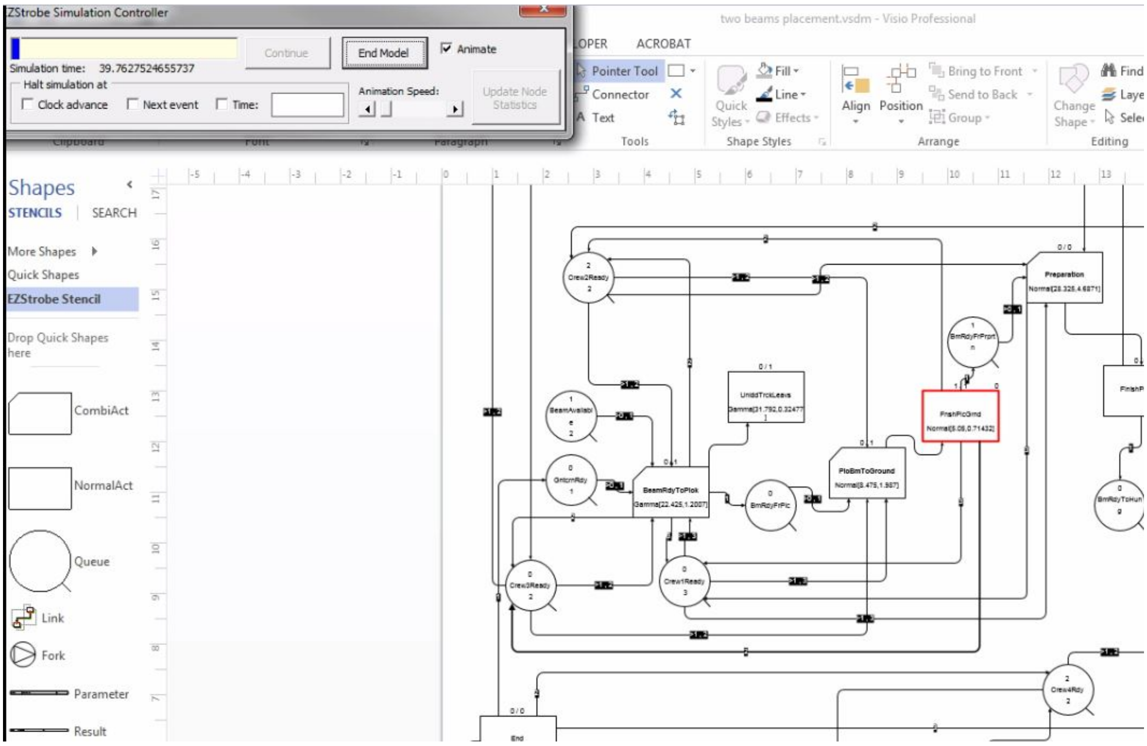

Figure A39 System State 39

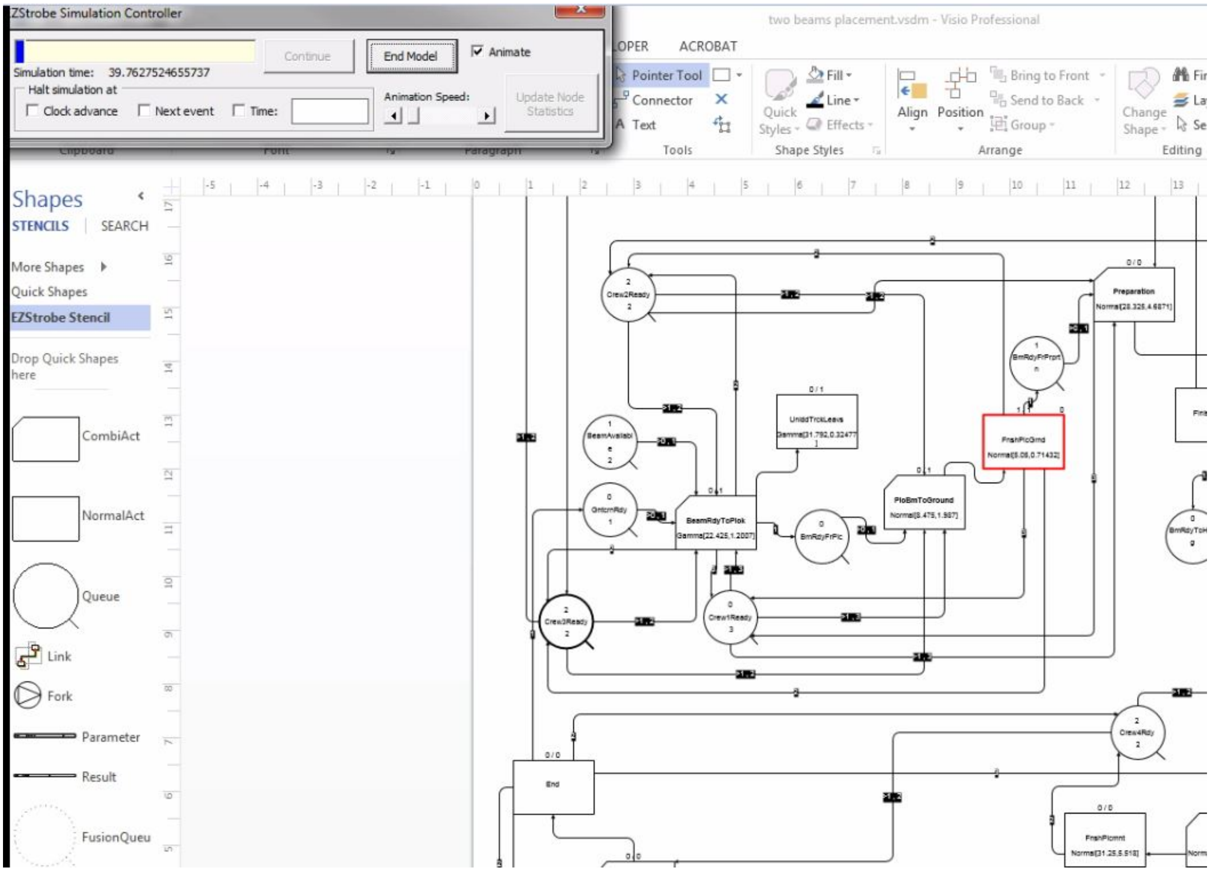

Figure A40 System State 40

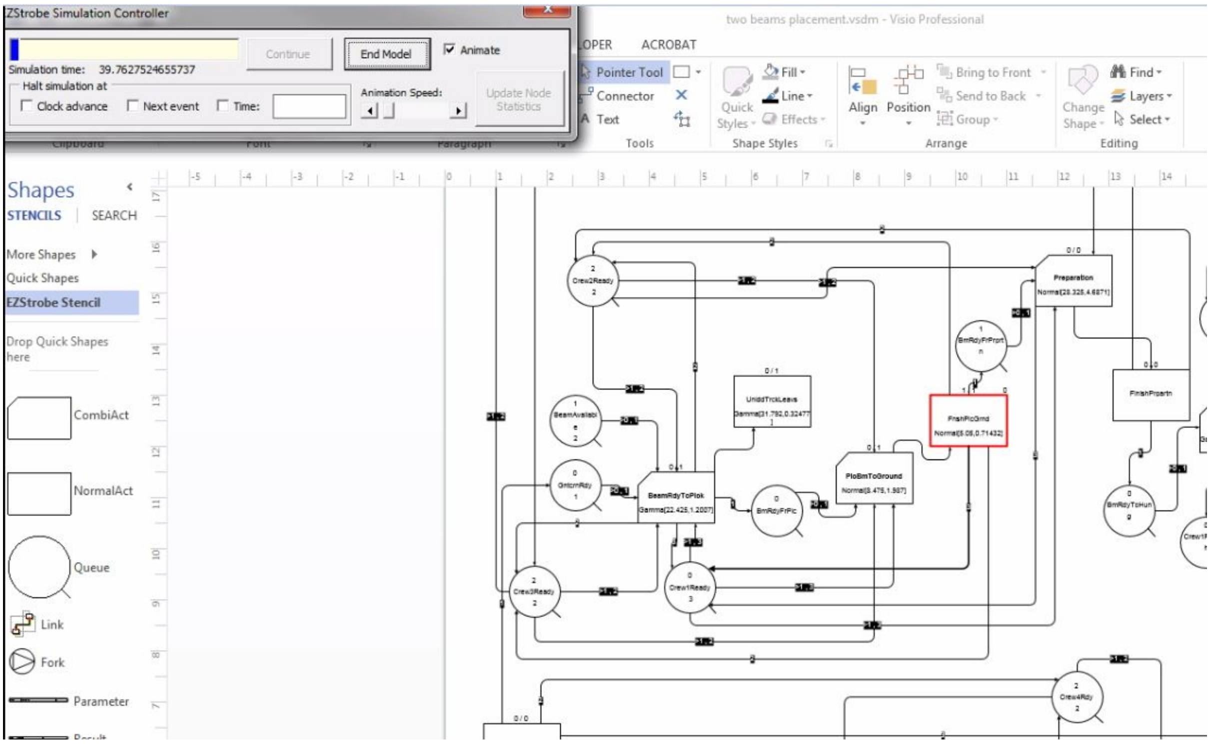

Figure A41 System State 41

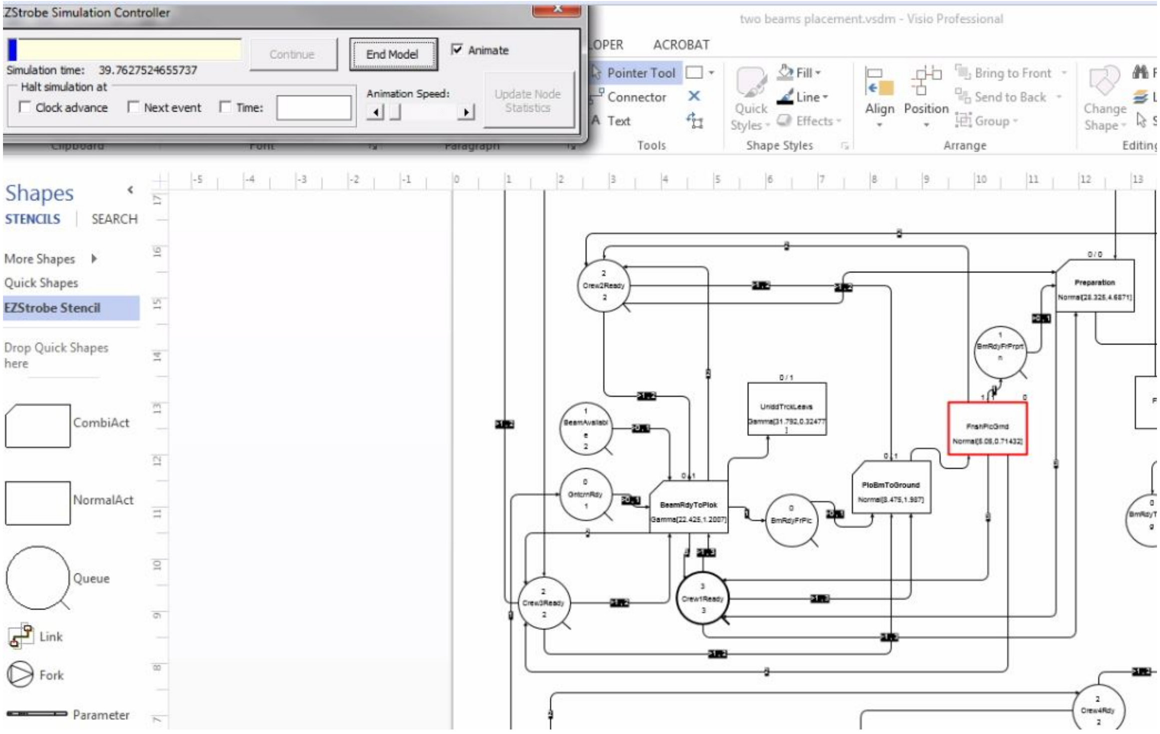

Figure A42 System State 42

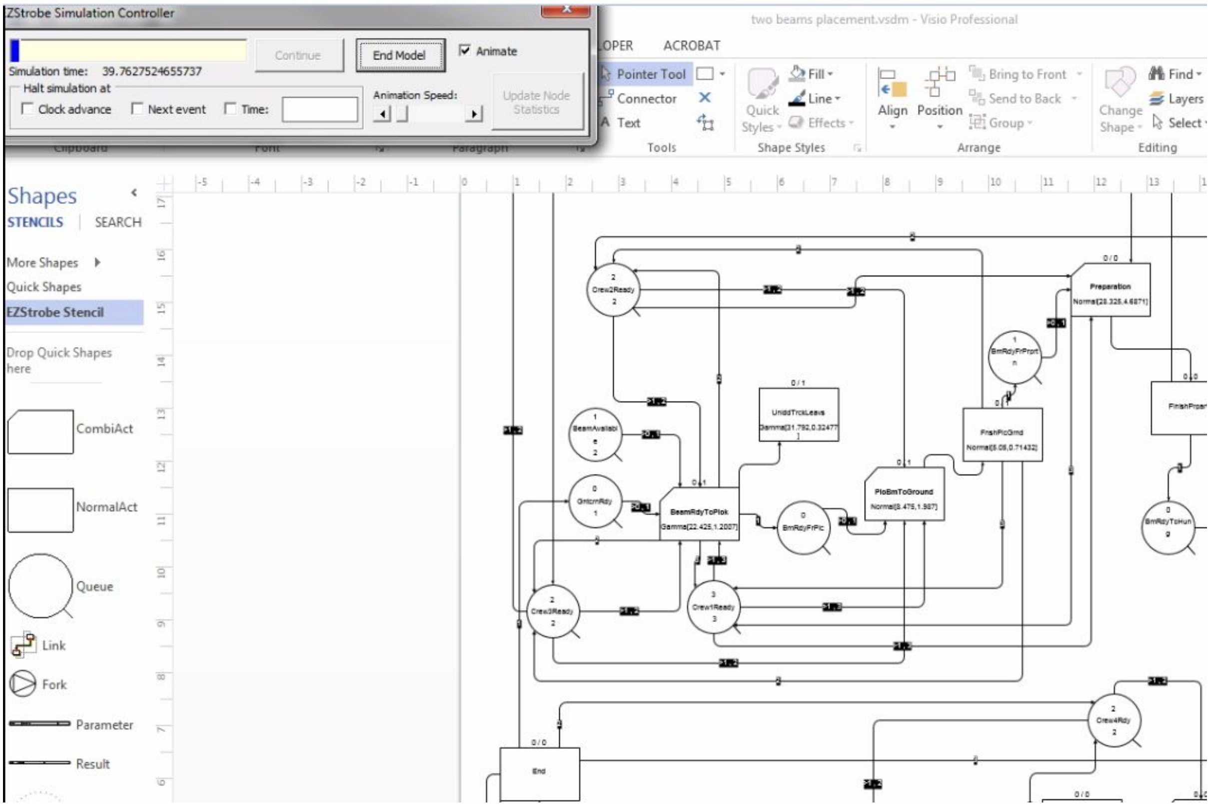

Figure A43 System State 43

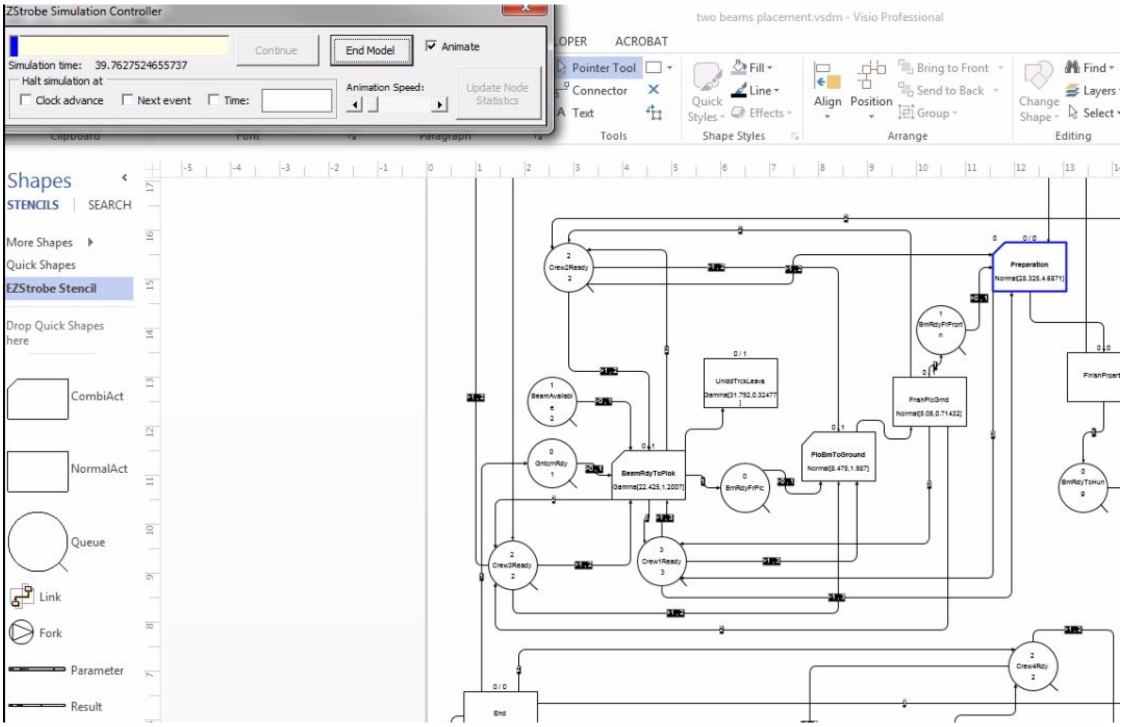

Figure A44 System State 44

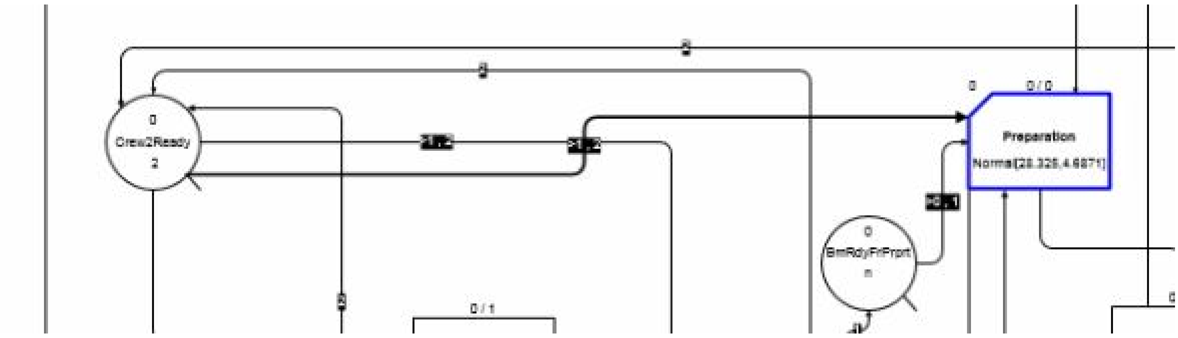

Figure A45 System State 45

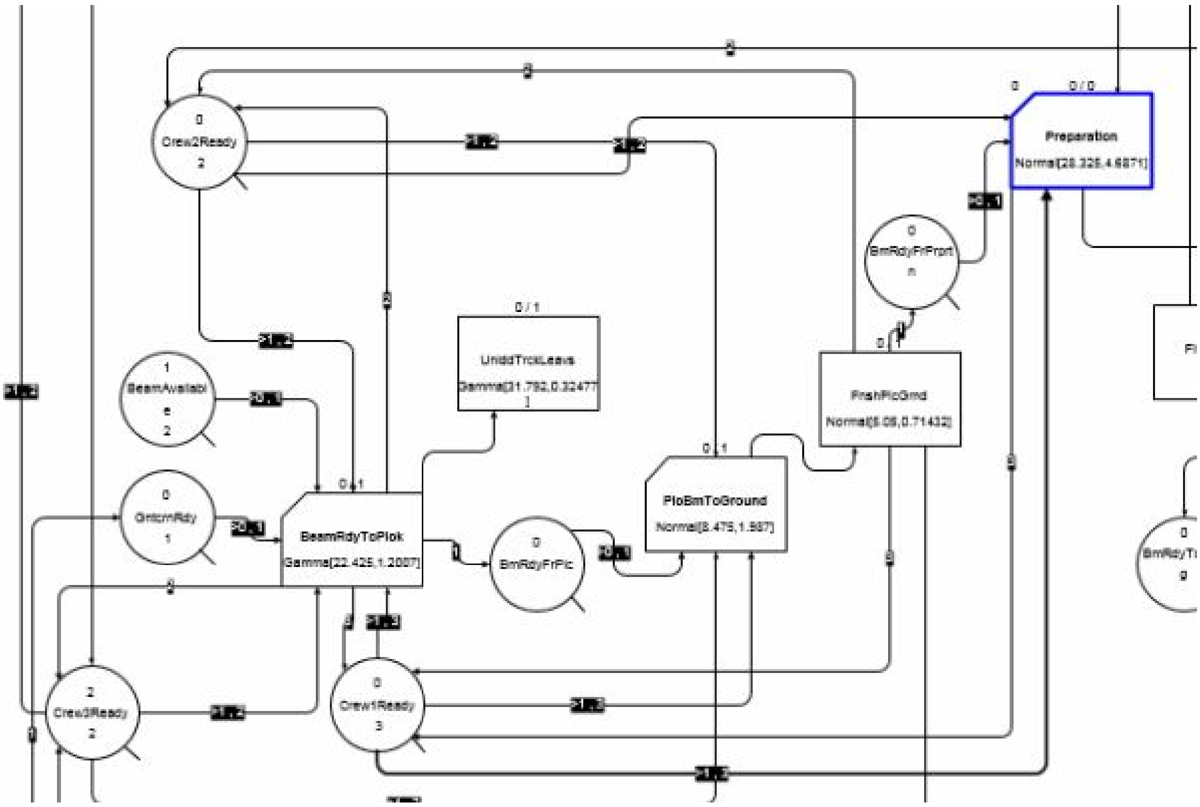

Figure A46 System State 46

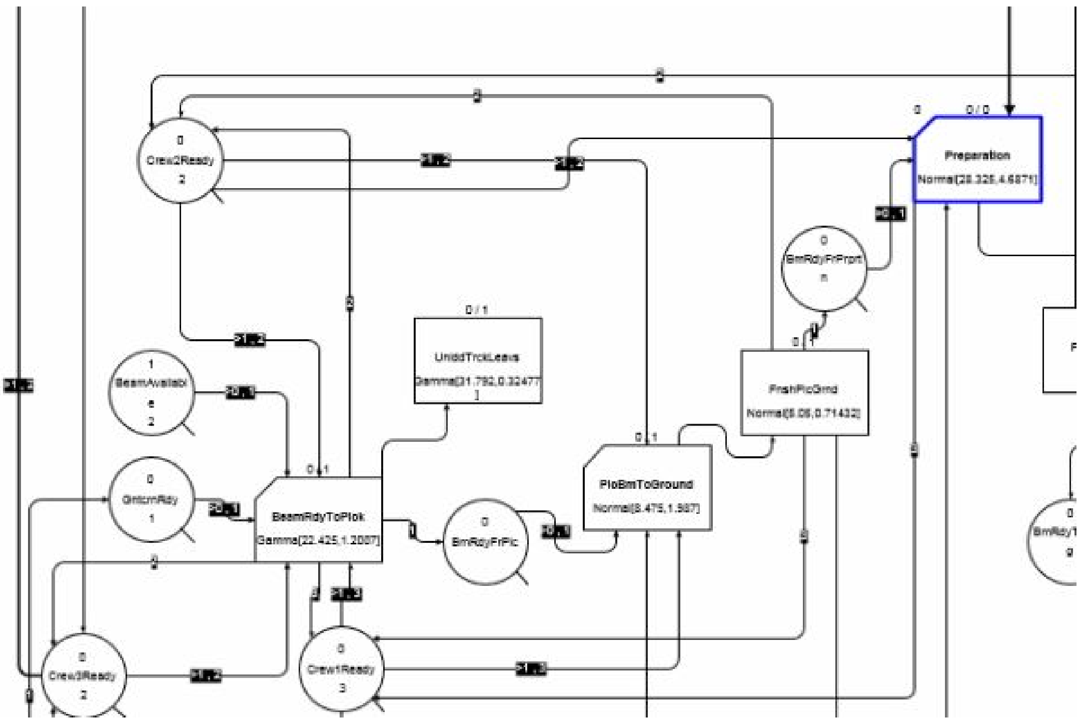

Figure A47 System State 47

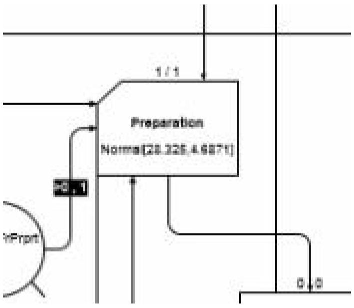

Figure A48 System State 48

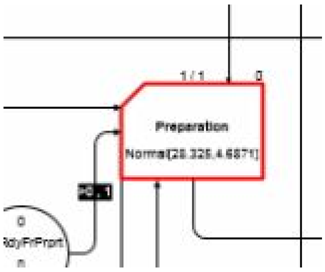

Figure A49 System State 49

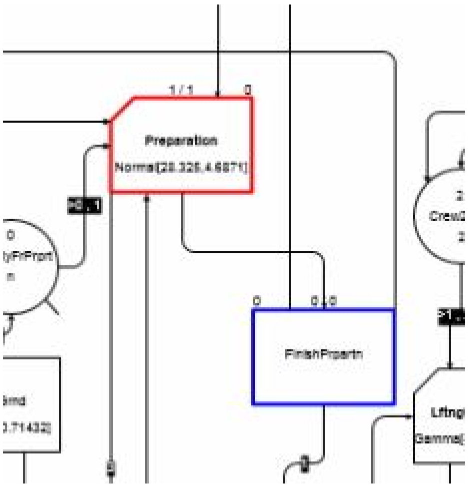

Figure A50 System State 50

APPENDIX 4 BEST FIT DISTRIBUTIONS (PDF ANALYSIS): COLLECTED DATA ON RAMPS 1 AND 4 TO NORMALISE THE SIMULATED MODEL

Fitting the Probability Distribution Functions

The data related to the activities included in the model developed and discussed in Section 7.4 are analysed using the EasyFit program in this section. The next paragraph explains the process of fitting the distribution for each of the activities.

Firstly, the data collected on the construction of Ramps 1 and 4 were fed into the EasyFit program. Next, the Goodness of Fit summary reported by the EasyFit program helped to identify which distribution function was best suited to the data set. As the Goodness of Fit summary tables show, three tests were used for the best fit distribution analysis: Kolmogorov–Smirnov, Anderson–Darling and Chi-squared. The best fit distribution function is the one that has the highest rank in the Goodness of Fit results for at least two of these tests. In the next step, the results, in accordance with the rank for each of these three tests, can be sorted out and selected from the Goodness of Fit table. Finally, the details of the selected distribution function can be found in the Fitting Results table in EasyFit under the related tab.

On the following table, the distribution function analysis for each of the described activities included in the GNRI Strobe Model II (Figure 7.17) is summarised.

Table A3 Goodness of Fit Summary: BeamRdyToPick

BeamRdyToPick						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
PERT	0.17951	1	3.242	1	35.246	8
Beta	0.17979	2	44.652	8	17.829	1
Uniform	0.19985	3	44.786	9	N/A	
Triangular	0.21703	4	4.2592	2	28.244	7

Erlang (3P)	0.24693	5	5.3784	4	22.191	2
Normal	0.24723	6	5.2999	3	23.897	6
Gamma	0.26361	7	6.4199	6	22.554	3
Gamma (3P)	0.2676	8	5.9252	5	23.726	5
Erlang	0.27897	9	6.8268	7	23.612	4
Selected Distribution Function: PERT						

Fitting Results	
Distribution	Parameters
Beta	α_1=0.83251 α_2=0.64513 a=20.0 b=38.0
Erlang	m=28 β=1.0672
Erlang (3P)	m=118 β=0.53941 γ=-33.46
Gamma	α=28.244 β=1.0672
Gamma (3P)	α=108.68 β=0.55561 γ=-30.509
Normal	σ=5.6716 μ=30.141
PERT	m=34.74 a=4.3951 b=38.241
Triangular	m=35.0 a=16.185 b=38.862
Uniform	a=20.318 b=39.965

Table A4 Goodness of Fit Summary: UnlddTrckLeaves

UnlddTrckLeaves						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Uniform	0.18854	1	18.894	4	N/A	

Erlang	0.19129	2	3.3185	2	48.634	4
Gamma	0.20915	3	3.1241	1	46.48	3
Beta	0.21179	4	43.809	7	N/A	
PERT	0.21558	5	31.788	6	15.055	2
Normal	0.22516	6	3.9546	3	48.938	5
Erlang (3P)	0.25061	7	29.537	5	7.5146	1
Gamma (3P)	0.31282	8	46.809	8	N/A	
Triangular	No fit					

Selected Distribution Function: Uniform

Fitting Results

Distribution	Parameters
Beta	α_1=0.88505 α_2=2.5929 a=8.0 b=30.0
Erlang	m=12 β=0.99335
Erlang (3P)	m=1 β=4.3261 γ=8.0
Gamma	α=12.409 β=0.99335
Gamma (3P)	α=0.92531 β=3.9838 γ=8.0
Normal	σ=3.4992 μ=12.326
PERT	m=8.0 a=8.0 b=33.512
Uniform	a=6.2654 b=18.387
Triangular	No fit

Table A5 Goodness of Fit Summary: PlcbmToGround

PlcbmToGround						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Gamma	0.18549	1	3.2819	1	9.3619	6
Normal	0.19626	2	3.5141	2	8.3594	5
Gamma (3P)	0.2107	3	3.6059	3	6.5263	3
Beta	0.21182	4	3.6101	4	6.5345	4
Uniform	0.22684	5	12.009	8	N/A	
PERT	0.23483	6	4.4078	5	12.205	7
Erlang	0.25113	7	4.4769	6	3.0429	1
Erlang (3P)	0.28857	8	5.623	7	5.2006	2
Triangular	0.36453	9	15.725	9	50.114	8
Selected Distribution Function: Gamma						

Fitting Results	
Beta	α_1=4.2821 α_2=2384.5 a=3.7759 b=2644.4
Erlang	m=13 β=0.62621
Erlang (3P)	m=4 β=1.0884 γ=3.7406
Gamma	α=13.591 β=0.62621
Gamma (3P)	α=4.3828 β=1.0884 γ=3.7406
Normal	σ=2.3086 μ=8.5109
PERT	m=6.0706 a=4.925 b=22.451
Triangular	m=5.0 a=5.0 b=20.24
Uniform	a=4.5123 b=12.509

Table A6 Goodness of Fit Summary: FnshPlcGround

FnshPlcGround						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Gamma (3P)	0.27765	1	7.0447	1	9.2552	3
PERT	0.28238	2	8.574	7	41.978	7
Gamma	0.28567	3	7.4342	5	8.9826	1
Beta	0.28681	4	7.1048	2	9.1468	2
Erlang	0.29212	5	7.3961	4	35.172	5
Uniform	0.29274	6	39.162	9	N/A	
Normal	0.31664	7	8.5406	6	40.813	6
Erlang (3P)	0.32165	8	7.358	3	33.435	4
Triangular	0.41529	9	16.356	8	50.431	8
Selected Distribution Function: PERT						

Fitting Results	
Beta	α_1=11.533 α_2=2.1298E+7 a=1.3125 b=7.3283E+6
Erlang	m=16 β=0.32608
Erlang (3P)	m=7 β=0.45478 γ=1.9798
Gamma	α=16.234 β=0.32608
Gamma (3P)	α=7.2864 β=0.45478 γ=1.9798
Normal	σ=1.3138 μ=5.2935
PERT	m=4.4774 a=2.8671 b=11.543
Triangular	m=5.0 a=2.593 b=10.284
Uniform	a=3.0179 b=7.5691

Table A7 Goodness of Fit Summary: Prepartion

Prepartion						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Uniform	0.15576	1	20.665	9	N/A	
PERT	0.16253	2	2.1378	1	23.545	8
Triangular	0.16555	3	2.248	2	2.5492	3
Beta	0.1688	4	4.1578	8	21.641	7
Gamma (3P)	0.171	5	2.3729	4	21.5	6
Gamma	0.18153	6	2.3494	3	19.327	5
Normal	0.1932	7	2.4551	5	18.183	4
Erlang (3P)	0.21281	8	3.2447	6	0.18659	1
Erlang	0.21348	9	3.5528	7	0.29687	2
Selected Distribution Function: PERT						

Fitting Results	
PERT	m=27.008 a=17.013 b=48.366
Erlang	m=23 β=1.2159
Erlang (3P)	m=9 β=1.9675 γ=10.477
Gamma	α=23.816 β=1.2159
Gamma (3P)	α=9.3928 β=1.9675 γ=10.477
Normal	σ=5.9335 μ=28.957
Beta	α_1=1.3966 α_2=1.6626 a=17.1 b=42.0
Triangular	m=25.0 a=17.14 b=44.234
Uniform	a=18.679 b=39.234

Table A8 Goodness of Fit Summary: LftngUpprprdBm

LftngUpprprdBm						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Gamma (3P)	0.29893	1	7.4143	1	42.378	4
Uniform	0.30346	2	54.568	8	N/A	
Gamma	0.3192	3	7.739	2	44.686	5
Erlang	0.32403	4	8.4223	3	53.577	6
Normal	0.34125	5	8.8001	5	157.1	7
Erlang (3P)	0.36771	6	8.765	4	10.811	3
PERT	0.37785	7	23.659	6	8.9589	2
Beta	0.38364	8	40.617	7	8.9551	1
Triangular	No fit					
Selected Distribution Function: Gamma						

Fitting Results	
Beta	α_1=0.89731 α_2=3.7197 a=8.0 b=20.862
Erlang	m=23 β=0.45192
Erlang (3P)	m=2 β=1.4894 γ=7.509
Gamma	α=23.956 β=0.45192
Gamma (3P)	α=2.2271 β=1.4894 γ=7.509
Normal	σ=2.2119 μ=10.826
PERT	m=8.0 a=8.0 b=23.111
Uniform	a=6.995 b=14.657
Triangular	No fit

Table A9 Goodness of Fit Summary: FinishHungngBm

FinishHungngBm						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Normal	0.22001	2	4.2415	1	23.772	7
PERT	0.21523	1	5.0918	6	12.565	2
Beta	0.22086	3	4.247	2	23.759	6
Gamma (3P)	0.23646	4	4.4304	3	23.471	4
Uniform	0.23882	5	27.234	9	N/A	
Erlang (3P)	0.24386	6	4.5157	4	23.556	5
Gamma	0.24454	7	4.7891	5	23.134	3
Erlang	0.32232	8	7.9596	7	1.7319	1
Triangular	0.33637	9	8.4322	8	40.425	8
Selected Distribution Function: Normal						

Fitting Results	
Beta	α_1=5523.1 α_2=3602.1 a=-235.48 b=168.93
Erlang	m=19 β=0.46479
Erlang (3P)	m=102 β=0.20559 γ=-11.75
Gamma	α=19.995 β=0.46479
Gamma (3P)	α=110.82 β=0.19625 γ=-12.485
Normal	σ=2.0783 μ=9.2935
PERT	m=8.6806 a=4.2009 b=16.881
Triangular	m=10.0 a=3.8162 b=16.169
Uniform	a=5.6937 b=12.893

Table A10 Goodness of Fit Summary: BmRdyLnch

BmRdyLnch						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
PERT	0.21449	1	4.0147	5	14.648	3
Gamma (3P)	0.21895	2	3.6686	1	15.209	5
Erlang (3P)	0.21992	3	3.6996	2	15.35	7
Uniform	0.22075	4	49.736	8	N/A	
Normal	0.22204	5	3.7158	3	15.242	6
Triangular	0.22697	6	4.1935	6	14.284	2
Gamma	0.23901	7	4.007	4	15.174	4
Erlang	0.33342	8	7.2533	7	13.348	1
Beta	0.51829	9	90.936	9	N/A	
Selected Distribution Function: PERT						

Fitting Results	
Beta	α_1=1.4687 α_2=0.43661 a=3.6338 b=15.0
Erlang	m=12 β=0.78086
Erlang (3P)	m=58 β=0.36907 γ=-11.265
Gamma	α=12.848 β=0.78086
Gamma (3P)	α=77.131 β=0.31829 γ=-14.531
Normal	σ=2.7989 μ=10.033
PERT	m=9.8075 a=3.1736 b=17.776
Triangular	m=10.0 a=3.6697 b=16.578
Uniform	a=5.1847 b=14.881

Table A11 Goodness of Fit Summary: GntCrnStartLnch

GntCrnStartLnch						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Gamma	0.26314	1	6.5278	4	12.8	3
Gamma (3P)	0.27442	2	6.3352	1	12.72	1
Erlang (3P)	0.27746	3	6.3361	2	12.735	2
PERT	0.28077	4	6.8125	5	30.277	4
Normal	0.29357	5	6.5085	3	41.483	7
Uniform	0.30845	6	46.903	8	N/A	
Erlang	0.31001	7	7.4885	6	30.305	5
Beta	0.31062	8	47.039	9	N/A	
Triangular	0.34109	9	7.8137	7	40.211	6
Selected Distribution Function: Gamma						

Fitting Results	
Beta	α_1=0.8275 α_2=1.357 a=5.0 b=15.713
Erlang	m=13 β=0.71711
Erlang (3P)	m=47 β=0.38126 γ=-8.2578
Gamma	α=13.445 β=0.71711
Gamma (3P)	α=46.855 β=0.38162 γ=-8.2394
Normal	σ=2.6294 μ=9.6413
PERT	m=8.9921 a=3.7063 b=18.163
Triangular	m=10.0 a=3.5785 b=16.251
Uniform	a=5.087 b=14.196

Table A12 Goodness of Fit Summary: BmMvDwn

BmMvDwn						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Uniform	0.20057	1	38.852	9	N/A	
Erlang (3P)	0.21036	2	3.6996	3	14.483	6
Normal	0.2107	3	3.586	1	14.895	8
Beta	0.21785	4	3.6443	2	14.478	5
Gamma (3P)	0.2259	5	3.7409	4	14.576	7
PERT	0.23102	6	3.9596	5	13.951	3
Gamma	0.24614	7	4.3625	6	13.907	2
Triangular	0.25508	8	5.2812	7	14.236	4
Erlang	0.30645	9	6.0142	8	5.9953	1
Selected Distribution Function: Normal						

Fitting Results	
Beta	α_1=8.2459 α_2=10.753 a=-1.1702 b=46.469
Erlang	m=13 β=1.4379
Erlang (3P)	m=82 β=0.59255 γ=-28.883
Gamma	α=13.569 β=1.4379
Gamma (3P)	α=86.211 β=0.57267 γ=-29.876
Normal	σ=5.2967 μ=19.511
PERT	m=17.944 a=7.5309 b=37.453
Triangular	m=20.0 a=6.717 b=35.449
Uniform	a=10.337 b=28.685

Table A13 Goodness of Fit Summary: FnshPlcmnt

FnshPlcmnt						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Triangular	0.15061	1	2.6761	4	13.792	8
PERT	0.15827	2	2.5997	1	8.8647	2
Normal	0.15854	3	2.6459	3	11.126	3
Beta	0.16102	4	2.6197	2	8.7583	1
Erlang (3P)	0.16321	5	2.7815	6	13.177	7
Gamma (3P)	0.16545	6	2.6852	5	12.528	4
Gamma	0.17077	7	2.7823	7	12.848	6
Erlang	0.1758	8	2.8136	8	12.674	5
Uniform	0.17842	9	24.993	9	N/A	
Selected Distribution Function: PERT						

Fitting Results	
Beta	α_1=2.2739 α_2=2.887 a=17.858 b=48.198
Erlang	m=27 β=1.1538
Erlang (3P)	m=64 β=0.75264 γ=-16.609
Gamma	α=27.083 β=1.1538
Gamma (3P)	α=71.125 β=0.71162 γ=-19.357
Normal	σ=6.0048 μ=31.25
PERT	m=30.241 a=17.192 b=49.222
Triangular	m=30.0 a=17.647 b=46.681
Uniform	a=20.849 b=41.651

Table A14 Goodness of Fit Summary: GntryMveUp

GntryMveUp						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
PERT	0.24505	3	6.0948	6	68.894	8
Gamma (3P)	0.24318	2	4.7023	1	31.989	4
Beta	0.24209	1	4.7229	2	31.975	3
Gamma	0.25215	4	4.8295	3	33.613	5
Erlang (3P)	0.26419	5	6.0619	5	13.682	1
Triangular	0.28713	6	15.818	8	67.256	7
Uniform	0.2882	7	22.419	9	N/A	
Normal	0.29447	8	5.8742	4	33.905	6
Erlang	0.29748	9	8.3093	7	16.908	2
Selected Distribution Function: PERT						

Fitting Results	
Beta	α_1=6.0202 α_2=8.5438E+6 a=2.5353 b=1.0867E+7
Erlang	m=9 β=1.0313
Erlang (3P)	m=6 β=1.2161 γ=2.3391
Gamma	α=9.8753 β=1.0313
Gamma (3P)	α=6.4514 β=1.2161 γ=2.3391
Normal	σ=3.241 μ=10.185
PERT	m=7.8146 a=4.6384 b=26.027
Triangular	m=5.0 a=5.0 b=22.725
Uniform	a=4.5712 b=15.798

Table A15 Goodness of Fit Summary: GntryRdyBck

GntryRdyBck						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Erlang	0.27634	1	7.3093	1	47.268	7
Beta	0.27864	2	64.528	8	5.0899	2
Uniform	0.29671	3	67.716	9	N/A	
PERT	0.30866	4	63.433	7	11.481	3
Gamma	0.31329	5	7.3868	2	38.746	6
Normal	0.33567	6	8.6644	3	138.95	8
Erlang (3P)	0.33615	7	31.946	5	12.055	4
Triangular	0.36845	8	10.535	4	33.853	5
Gamma (3P)	0.50498	9	44.314	6	0.58143	1
Selected Distribution Function: Erlang						

Fitting Results	
Beta	α_1=0.51543 α_2=0.73245 a=8.0 b=15.0
Erlang	m=22 β=0.48523
Erlang (3P)	m=1 β=2.8922 γ=8.0
Gamma	α=22.446 β=0.48523
Gamma (3P)	α=0.65332 β=2.9944 γ=8.0
Normal	σ=2.2989 μ=10.891
PERT	m=8.0 a=8.0 b=24.693
Triangular	m=10.0 a=6.9692 b=16.55
Uniform	a=6.9096 b=14.873

Table A16 Goodness of Fit Summary: GntryPushBck

GntryPushBck						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Normal	0.14475	2	1.8765	1	6.3713	5
Beta	0.14427	1	1.8811	2	6.1671	3
PERT	0.14482	3	2.0496	5	5.9127	2
Erlang (3P)	0.15091	4	1.9681	4	6.3733	6
Triangular	0.15223	5	2.9753	8	5.7477	1
Gamma (3P)	0.15293	6	1.9181	3	6.3547	4
Uniform	0.15929	7	10.49	9	N/A	
Gamma	0.1796	8	2.4318	6	6.48	8
Erlang	0.20103	9	2.7519	7	6.3769	7
Selected Distribution Function: Normal						

Fitting Results	
Beta	α_1=9.8439 α_2=9.9741 a=-8.3135 b=48.798
Erlang	m=10 β=1.972
Erlang (3P)	m=106 β=0.60991 γ=-44.296
Gamma	α=10.17 β=1.972
Gamma (3P)	α=88.74 β=0.66739 γ=-39.185
Normal	σ=6.2886 μ=20.054
PERT	m=20.091 a=2.5119 b=37.471
Triangular	m=20.163 a=4.0 b=35.0
Uniform	a=9.1622 b=30.947

Table A17 Goodness of Fit Summary: FinishLocking

FinishLocking						
Goodness of Fit Summary						
Distribution	Kolmogorov–Smirnov		Anderson–Darling		Chi-squared	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Uniform	0.19326	1	22.467	4	N/A	
Normal	0.22545	2	5.2254	1	15.121	1
Gamma	0.2426	3	6.4465	2	21.291	3
Erlang	0.25372	4	6.607	3	19.883	2
Triangular	0.34783	5	202.68	8	77.681	5
Erlang (3P)	0.34789	6	125.39	6	67.672	4
Beta	0.41699	7	74.328	5	124.64	6
Gamma (3P)	0.52425	8	191.59	7	N/A	
PERT	No fit					
Selected Distribution Function: Normal						

Fitting Results	
Beta	α_1=0.21325 α_2=1.1806 a=5.0 b=17.815
Erlang	m=8 β=1.0286
Erlang (3P)	m=1 β=2.6552 γ=5.0
Gamma	α=8.19 β=1.0286
Gamma (3P)	α=0.18988 β=6.7516 γ=5.0
Normal	σ=2.9435 μ=8.4239
Triangular	m=5.0 a=5.0 b=16.105
Uniform	a=3.3255 b=13.522
PERT	No fit

APPENDIX 5 UNDERSTANDING THE SYSTEM BEHAVIOUR: MODELLING DIFFERENT SCENARIOS

Construction operations are exposed to different constraints, including weather conditions, lack of resources, etc. Consequently, the current research aimed to explore how EZStrobe would be capable of helping construction project planners to understand the system behaviour in different conditions, for example, identifying the operation cycle time by accounting for constraints on the system behaviour. In this section, one of the most apparent constraints raised, namely, the lack of resources, has been selected for modelling by this study. In the studied case project, as discussed in Section 6.1, one of the main components of the gantry machine is auxiliary support. The gantry machine designed for this specific project in New Zealand was supplied with one auxiliary support.

As the distance to the launching destination is dependent on the location of auxiliary support, in progressing the operation toward new spans, the auxiliary support needed to be relocated. In the following section, that necessity has been considered through a new scenario that was simulated and presented.

Need to move Auxiliary Support

As the operation proceeded, the auxiliary support needed to be moved with the rollers moved forward to enable the processes of beam launching and placement for further spans. The need was due to the limited amount of equipment supplied to the studied project. However, this caused the addition of an extra process in the operation.

To complete this process, the required machine resources were identified, as presented in Table A18.

Table A18 Information on Queues and their descriptions

Resource Annotation	Quantity	Descriptions
C1Rdy	3	These two crews are ready to prepare the floor for the placement of auxiliary support.
C2Rdy	2	
LddTrc	1	As usual, every day in the early morning the loaded truck comes to the gantry area and delivers the beam to the site. Then the availability of the loaded truck is part of the real-world project, while it is not a real condition for the movement of auxiliary support.
TDriverRdy	1	As explained above, the driver leaves the site when he delivers the loaded truck to the site. The driver cannot stay at the site until the project starts. The operation is either scheduled in day shift or night shift: the driver does not waste time and,

Resource Annotation	Quantity	Descriptions
		immediately after delivering the beam to the site, he leaves. Therefore, in the condition that the loaded truck is on site, and moving the auxiliary support needs to be done, the truck driver should be back to the site to move the truck.
JLGRdy	1	This machine should be available at the site for moving the elements of the auxiliary support.
FloorRdy		This Queue has been included in the model only to emphasise the need for the preparation of the floor before settling down the auxiliary support in the new place.

The sequences of the activities and the duration of their completion according to the concept of the real-world project were in accordance with the information presented in Table A19.

Table A19 Information on Activities

	Activity	Duration (minutes)
1	PrprtnFlrAuxSpr	30
2**	AuxlSprtStrtMve	30
3**	JLGMvFrwrd	10
4	AuxSprtinNewPlc	40
5	LddTrkMveFwrd	15
6	LddTrkUndrCrne	20
7	BmPickUp	20-25*
8	UnlddTrkLeave	10-15*
9	PlcBmToGrnd	10-15*
10	FnshPlGrnd	3-7*

*The durations of these activities have been included in the model using the probability distribution function (PDF) as further data for the PDF analysis were available. For the rest of the activities, the collection of data occurred the first time that this process was carried out in the real-world operation.

** These two activities start at the same time. As the start of Activity 4 (Ac.4) is dependent on the completion of both Ac.2 and Ac.3, Ac.4 can then start at time 40.

The study has followed the steps for model development and simulation of this scenario as discussed in Section 7.2. STROBOSCOPE was run and the output for the Queues and Activities was as summarised in Table A20 and A21.

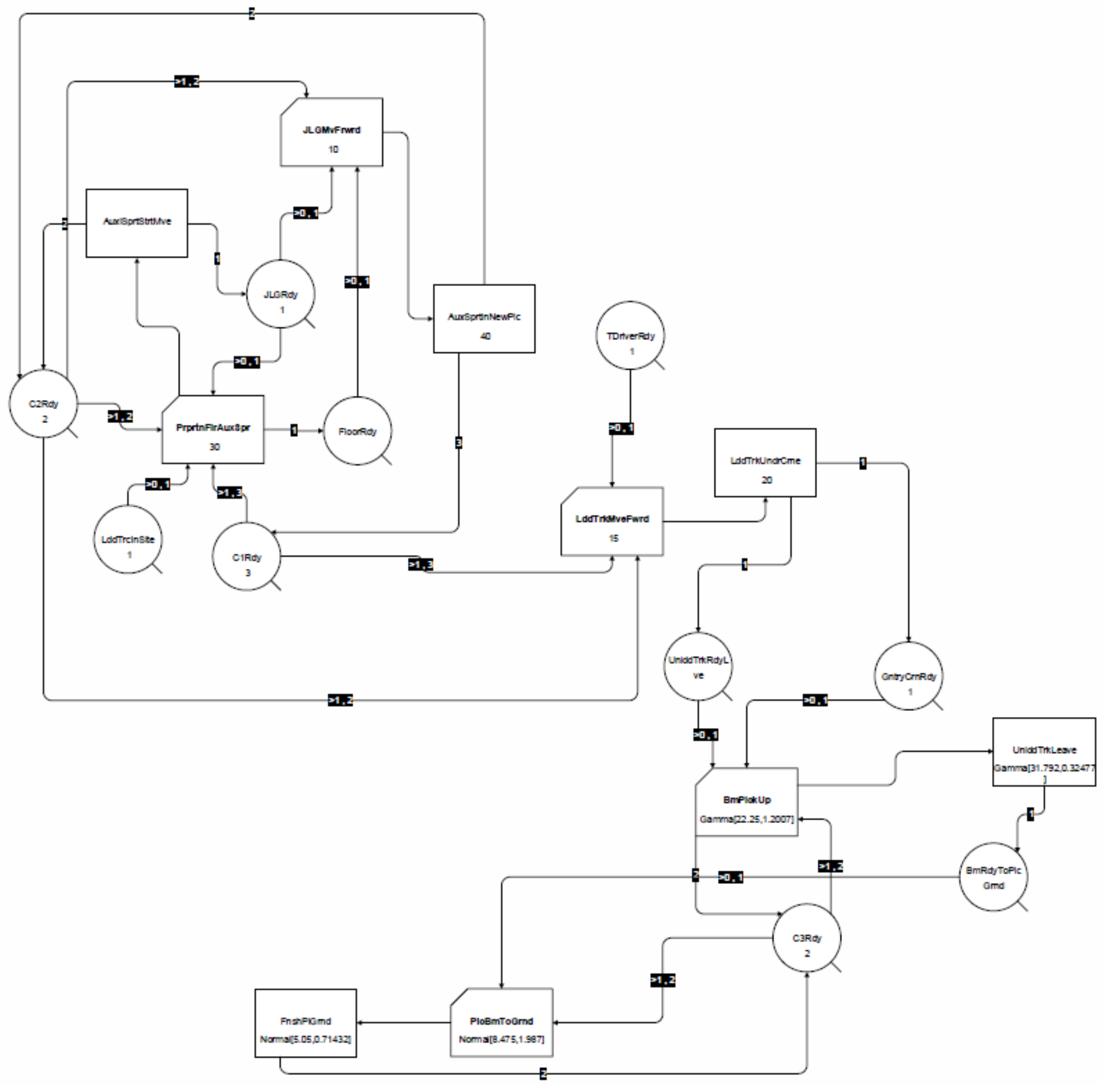

Figure A51 Scenario I: Need for extra work/moving auxiliary support

Table A20 Queues' output

Queue	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
BmRdyToPlcGrnd	0.00	1.00	0.00	0.00	0.00	0.00	1.00
C1Rdy	0.00	6.00	0.00	0.00	0.00	0.00	3.00
C2Rdy	0.00	6.00	0.00	0.00	0.00	0.00	2.00
C3Rdy	2.00	6.00	42.28	1.52	0.85	0.00	2.00
FloorRdy	0.00	1.00	0.00	0.00	0.00	0.00	1.00
GntryCrnRdy	1.00	2.00	83.21	1.00	0.00	1.00	2.00
JLGRdy	0.00	2.00	0.00	0.00	0.00	0.00	1.00
LddTrcInSite	0.00	1.00	0.00	0.00	0.00	0.00	1.00
TDriverRdy	0.00	1.00	80.00	0.48	0.50	0.00	1.00
UnlddTrkRdyLve	0.00	1.00	0.00	0.00	0.00	0.00	1.00

Table A21 Activities' output

Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur	MinD	MaxD	AvInt	SDInt	MinI	MaxI
AuxSprtinNewPlc	0.00	1.00	40.00	40.00	40.00		40.00	40.00				
AuxlSprtStrtMve	0.00	1.00	30.00	30.00	0.00		0.00	0.00				
BmPickUp	0.00	1.00	115.00	115.00	22.74		22.74	22.74				
FnshPlGrnd	0.00	1.00	161.37	161.37	5.04		5.04	5.04				
JLGMvFrwrd	0.00	1.00	30.00	30.00	10.00		10.00	10.00				
LddTrkMveFwrd	0.00	1.00	80.00	80.00	15.00		15.00	15.00				
LddTrkUndrCrne	0.00	1.00	95.00	95.00	20.00		20.00	20.00				
PlcBmToGrnd	0.00	1.00	149.58	149.58	11.79		11.79	11.79				
PrprtnFlrAuxSpr	0.00	1.00	0.00	0.00	30.00		30.00	30.00				
UnlddTrkLeave	0.00	1.00	137.74	137.74	11.84		11.84	11.84				
					166.41							

As the output shows, the cycle time for this process was almost three hours. Therefore, this scenario helped the management/planning team in the studied case project to understand how many extra hours, in addition to the hours required for the completion of the launching and placement of the beam, might be required due to the limited amount of equipment (as one of the constraints).

Moreover, this research could present another capability of EZStrobe in providing the project team with a clear picture of the system in different conditions prior to the system experiencing that condition in the real world. This clear picture supports the project team when making their decisions on the application of solutions to have better control over different conditions. For example, they could include these extra hours in their master plan, or daily plan, and consequently decide how many crews, what other resources and when they should be utilised in order to handle the extra work as the operation progressed.

APPENDIX 6 CONTRIBUTION OF THE STUDY TO IMPROVE IMPLEMENTATION OF THE LAST PLANNER SYSTEM TOOL

As explained in Section 5.4, this study developed the spreadsheet database to collect and utilise data in simulating the studied operation. The recorded data were found to be useful from the management perspective as they could provide the project management team with a history of system behaviour. Through the data being referred to by the review of the system behaviour, a clearer picture of the system was captured, with the reasons for different behaviours identified. One of the significant contributions of the utilisation of these data happened through the implementation of the Last Planner System (LPS). The database could help with automating the Last Planner (LP) measurement in the studied case by providing the project team with a measurement platform for the LP's component: "Plan Percentage Completion, and Constraints".

Finally, the historical data utilised for the implementation of the LPS supported the project team to identify the most common constraints in the gantry launching operation. The following list was prepared and communicated to the planning team to account for the impacts of these constraints on the progress of the gantry launching operation (for the GNRI):

1- weather
2- lack of resources (plant/labour/materials/survey, etc.)
3- documentation (CEP [construction engineering products]/RFI [request for information], etc.)
4- deliveries
5- TW (temporary work) design
6- PW (permanent work) design
7- traffic closures
8- completion by other trades
9- access
10- unrealistic target
11- change to plan
12- defect/rework
13- unforeseen event (ground conditions/unknown service)
14- predecessor
15- planning clash

16- communication between the teams/personnel

The project team went beyond this analysis, and measured the probability of the occurrence of these constraints to answer this question: “what is the correlation between constraints and plan percentage completion?” Using the automated MS Excel spreadsheet and accessing the simulation spreadsheet database (see Section 5.4), the research study could provide the project team with a graphical report, as presented in Figures A52 and A53.

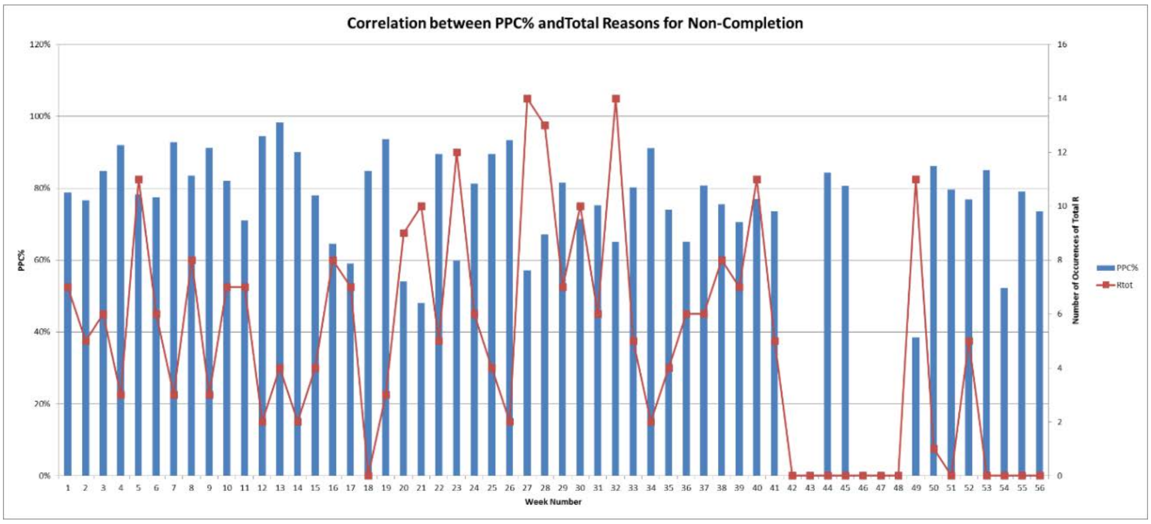

Figure A52 Impact of reasons for non-completion on the trend of project percentage completion (PPC)

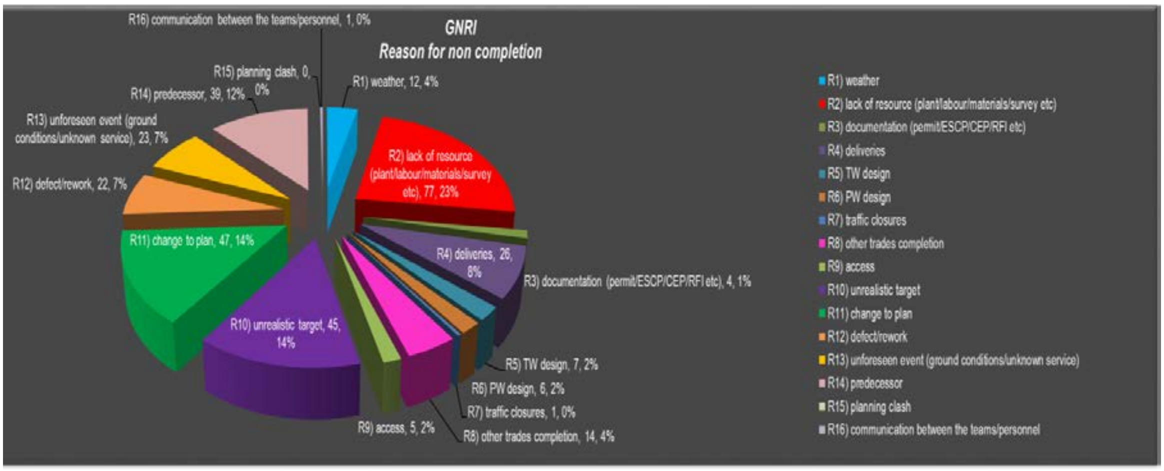

Figure A53 Weekly root causes analysis report graph

These graph representations provide the case project’s planners and managers with understanding on how and to what extent the different variations (constraints) listed above affected the project delivery rate. The average of the impact of variations is shown as Rtot in Figure A52. When Rtot has been well controlled, it can be seen that project percentage completion (PPC) improved significantly. Thus, the planning team could take more variations into account to achieve a more reliable plan, and consequently manage the project time frame well to complete the project a few weeks earlier than the estimated due date. The contribution of this research has been recognised by and has gained the approval of the case project organisation which published details of the research study in its Fatigue Management Report (see Figure A54).

Fatigue Management Report

PhD Student

The project team invested in a PhD student; a unique experience for the site team but with great effect that lead to great results.

Our research student was developing a simulation model to give us the maximum utilization of the beam launching gantry (Dennis). This PhD student discussed and shared the results of the modelling with the project manager, and some other team member in gantry operations regularly.

Modelling the launching operations under different conditions helped the site managers and planning team breaking down the daily plan into hourly plan. Consequently, dividing the gantry operations tasks into different shift with the purpose of fatigue control.

Along with gaining a better understanding of the gantry operations, the implementation of Last Planner become at the center of attention.

Studying the Gantry operations by our research student demonstrated that to improve productivity, in addition to operations behavior analysis, the project requires access to a proper database. Database serves as a platform which let the project reviewing the historical data, and access data at any time for any further needs such as Last Planer implementation.

With the use of Spreadsheet database, few issues in the use of Last Planner have been raised: inaccurate/ incorrect data entry, insufficient detail, poor collaboration between Engineers and supervisors, inaccurate measurement of the Last Planner element (especially PPC). However, the need for automating the Excel Spreadsheet become apparent. Through the automated version, human fault on data entry, and measurement were improved.

Overall collaboration of the research at the level of scheduling includes:

- Supporting the project team with developing high level schedule,
- Enhancing the reliability of LP data,
- Identifying the variations/ constraints,
- Identifying the tasks with slow progress, and making decision on how those tasks can be accomplished better (decisions included change the sequences of activities, change in the method of construction, etc.)

The new experience with the engagement of research student helped with increasing the rate of the productivity in our project as well as achieving excellent safety performance.

Figure A54 Contribution of the research study in the case organisation