AN INTERACTIVE CONSTRUCTION

DEPLOYMENT PLANNING MODEL FOR THE

SKA PROJECT

by

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Declaration

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Abstract

The *Square Kilometre Array (SKA)* is a global project to build the world's largest telescope that stretches over at least 3000 km. There is a number of factors that need to be considered during the planning of the construction deployment of the SKA antenna foundation infrastructure on a site as enormous as SKA. This study presents (1) a review on alternative approaches to increase the construction operational and resource efficiency by means of an optimization planning model; and (2) the development of a construction deployment planning tool which can be used by a construction manager during the site layout planning and the scheduling of repetitive activities. The developed prototype decision support software is designed as an interactive management system that provides a graphical user interface and 2D visual communication. This approach allows for human judgement and the experience of an expert to be captured during the site layout planning and scheduling of the repetitive construction activities. The construction deployment planning model describes the integration of a simulation-based site layout planning (SLP) model and a repetitive project scheduling (RPS) model.

The simulation-based SLP model facilitates the manual optimization of the site layout. The optimization procedure is performed with a series of "what if" analyses during the layout of temporary construction facilities in order to minimize site transportation cost/time, site establishment cost and to improve the efficiency of material handling on site. The model makes use of unique concepts to connect material sources (temporary facilities) and demand destination on site in a continuous 2D space. It is these connections that determine the dynamic flow of resources between temporary construction facilities and demand destination.

The RPS model facilitating the manual optimization of multiple objectives (1) minimizes the project duration; (2) maximizes resource utilization; while (3) maintaining a feasible labour cost. The RPS model automatically generates a project schedule by utilizing a flexible algorithm for resource-driven scheduling. The algorithm identifies the scheduled starting and finishing times for each activity in the repetitive units. The algorithm allows for: (1) multiple activity crew assignment to perform work simultaneously; and (2) the assignment of a specific crew work interruption time.

The model uses unique concepts to facilitate integration of site layout planning, material supply and project scheduling. These concepts allow for automatic scheduling of the activities at any number of repetitive units and integrating the activity information at a repetitive unit with the material supply information (i.e. concrete, steel, shutters etc.) at the demand destination. Accordingly, the impact of a site layout on the project schedule can be shown.

Uittreksel

Die Square Kilometre Array (SKA) is `n wêreldwye projek om die wêreld se grootste teleskoop, wat minstens oor 3000 km strek, te bou. Daar is `n aantal faktore wat in ag geneem moet word tydens die beplanning van die konstruksie van die antenna fondamente, op `n terrein so enorm soos SKA. Hierdie studie bied (1) `n oorsig oor alternatiewe benaderings deur middel van `n optimeringsmodel, tot die verbetering van konstruksie en hulpbron-doeltreffendheid; en (2) die ontwikkeling van `n model wat deur `n konstruksie-bestuurder gebruik kan word tydens die beplanning van die terreinuitleg en skedulering van die herhalende aktiwiteite. Die ontwikkelde prototipe sagteware kan gebruik word om besluite te ondersteun en is daarom ontwerp as `n interaktiewe stelsel wat `n grafiese gebruikerskoppelvlak en 2D visuele kommunikasie bied. Hierdie interaktiewe benadering maak voorsiening dat menslike oordeel en die ervaring van `n kenner in die model opgeneem kan word. Die konstruksie-ontplooing beplanningsmodel beskryf die integrasie van n "Site Layout Planning (SLP)" model en `n "Repetitive Project Scheduling (RPS)" model.

Die simulasie-gebaseerde SLP model fasiliteer die optimering van die konstruksie terrein deur die gebruiker. Die optimeringsprosedure word uitgevoer met `n reeks "sê-nou-maar" ontledings tydens die plasing van die verskeie tydelike konstruksie-fasiliteite op die terrein. Die fasiliteite word geplaas en gerangskik om die vervoertyd en -koste, en die konstruksieterrein vestigingskoste te minimeer, asook om die doeltreffendheid van materiaalhantering op die terrein te maksimeer. Die model maak gebruik van unieke konsepte om materieële bronne (tydelike fasiliteite) en bestemmings te koppel in `n deurlopende 2D ruimte op die terrein. Dit is hierdie verbindings wat die dinamiese vloei van hulpbronne tussen tydelike konstruksiefasiliteite en bestemmings (antennafondamente) bepaal.

Die RPS model fasiliteer die optimering van die projekskedule in terme van veelvuldige doelwitte: (1) verminder die konstruksie tydperk; (2) maksimeer hulpbronbenutting; en (3) die handhawing van `n uitvoerbare arbeidskoste. Die RPS model genereer outomaties die projek-skedule deur gebruik te maak van `n hulpbron-gedrewe skedulering-algoritme. Die algoritme identifiseer die geskeduleerde begin en eindtye vir elke aktiwiteit in die herhalende eenhede. Die algoritme maak dit moontlik dat: (1) aktiwiteite gelyktydig deur verskeie spanne uitgevoer word; en om (2) `n spesifieke werk-onderbrekingstyd aan werkspanne te spesifiseer.

Die model maak gebruik van unieke konsepte om die integrasie van die terreinuitleg, beplanning, materiaal verskaffing en projekskedulering te fasiliteer. Gevolglik kan die impak van `n konstruksieterrein uitleg op die projekskedule aangetoon word

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List of Abbreviations

SKA	Square Kilometre Array
SKA1	Square Kilometre Array Phase 1
SKA2	Square Kilometre Array Phase 2
INFRA SA	Infrastructure South Africa Consortium
MeerKAT	64-dish Karoo Array Telescope
SKAO	Square Kilometre Array Organisation
SLP	Site layout planning
RPS	Repetitive project scheduling
RMC	Ready Mix concrete
F	Antenna foundation unit
GUI	Graphical user interface
UML	Unified Modelling Language
OR	Operational research

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CHAPTER 1

Introduction

1.1 Subject

This thesis describes the alternatives explored to improve the efficiency of construction operations on the SKA site and the development of a decision support model in order to effectively plan the construction deployment of the SKA antenna foundations.

1.2 Background on SKA

The Square Kilometre Array (SKA) project is an international collaboration to build the world's largest radio telescope, with a square kilometre (one million square metres) collecting area. It will be the world's first radio telescope array consisting of composite antenna structures. The project entails the deployment of thousands of radio telescopes, in three unique configurations, that will enable astronomers to monitor the sky in unprecedented detail and to survey the entire sky thousands of times faster than any system currently in existence. The SKA project will not only be located on one or two sites, however. The many elements and sub-elements will be spread out across thousands of kilometres on the selected sites and even across the globe. For more information about SKA South Africa, the reader is referred to (SKA South Africa, 2015b)

Two precursory projects have been completed in South Africa, located approximately 90 km outside the small Northern Cape town of Carnarvon (Karoo). The first was KAT-7 which entailed the installation of the world's first 7 fibre glass dishes. KAT-7 was completed by December 2010 and has already delivered images of the Centaurus A, a galaxy 14-million light years away. KAT- 7 was super ceded by the 64-dish MeerKAT. MeerKAT has a total of 64 dishes which will be incorporated into the 190 dishes of SKA phase one (SKA 1), resulting in a total of 254 dishes for SKA1. The MeerKAT infrastructure and power elements have been built in such a way as to allow for further extension of SKA1 (T. Lekalake, 2014). For more information about the MeerKAT, refer to (SKA South Africa, 2015a). The primary development and construction phases of the project are split into Phase1 and Phase2, known as SKA1 and SKA2 (Stevenson & Spyromilio, 2013). The construction of SKA2 will commence during the operations phase of SKA1 (see Figure 2.1). More information in this regards this is given in Chapter 2: Project phases and transitions.

Overview of the Scope

The SKA organisation is divided into different Consortia as shown in Figure 1.1. The INFRA-SA Consortium which is considered in this study is responsible for the design and construction of the infrastructure and power for SKA 1. The main elements of the infrastructure and power for SKA 1 are shown in Figure 1.1:
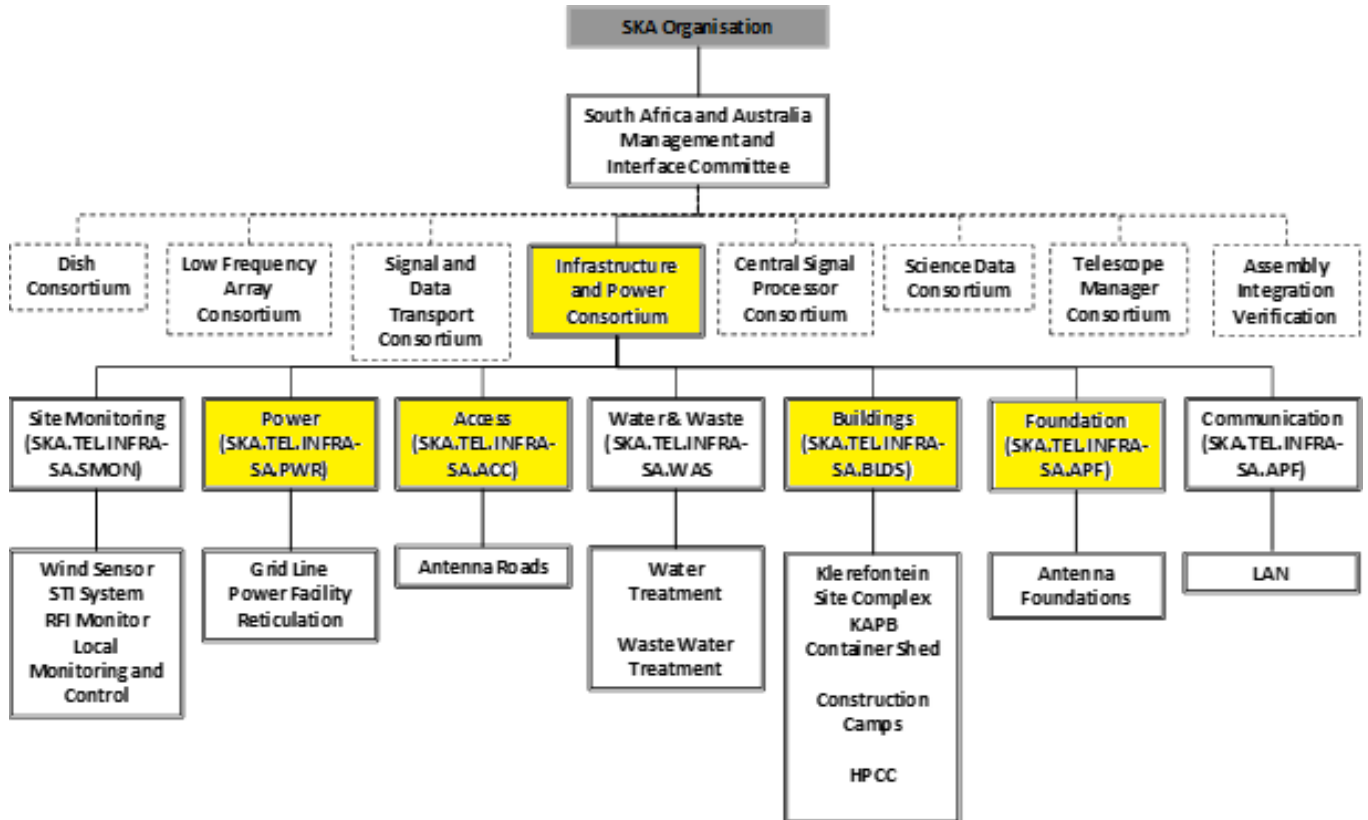
Figure 1.1: Infrastructure and Power Sub-Elements

This study is focused around the construction deployment of the dish *Foundations* (i.e. antenna platform foundations) of the INFRA-SA Consortium, highlighted in Figure 1.1. The latest configuration of the SKA1 (incorporating MeerKAT) dishes is shown in Figure 1.2.

The conceptual approach to the construction deployment methodology is to divide the configuration into three areas, namely, the inner core (the centre which has most of the antennas), the outer core and the three spiral arms. The following deployment is proposed by INFRA-SA (T. Lekalake, 2014).The collecting area of each of the locations has been identified based on the work by Bolton, Millenaar and Harris (February 2011); Millenaar and Dewdney (February 2010

No. of dishes	Location	Collecting area	Date of required access
80	Inner Core	radius 2.5km	2018/01/15
80	Outer Core	2.5km-5km	2019/01/15
30	Spirals	5 km-100km	2019/06/30

This implies that at the required dates of access the foundations must have been completed and ready for the installation of dishes. Figure 1.3 shows the available construction duration for each of the three construction areas, based on the start and finish dates proposed by INFRA-SA, taking into consideration no-working days (i.e. weekends and holidays).
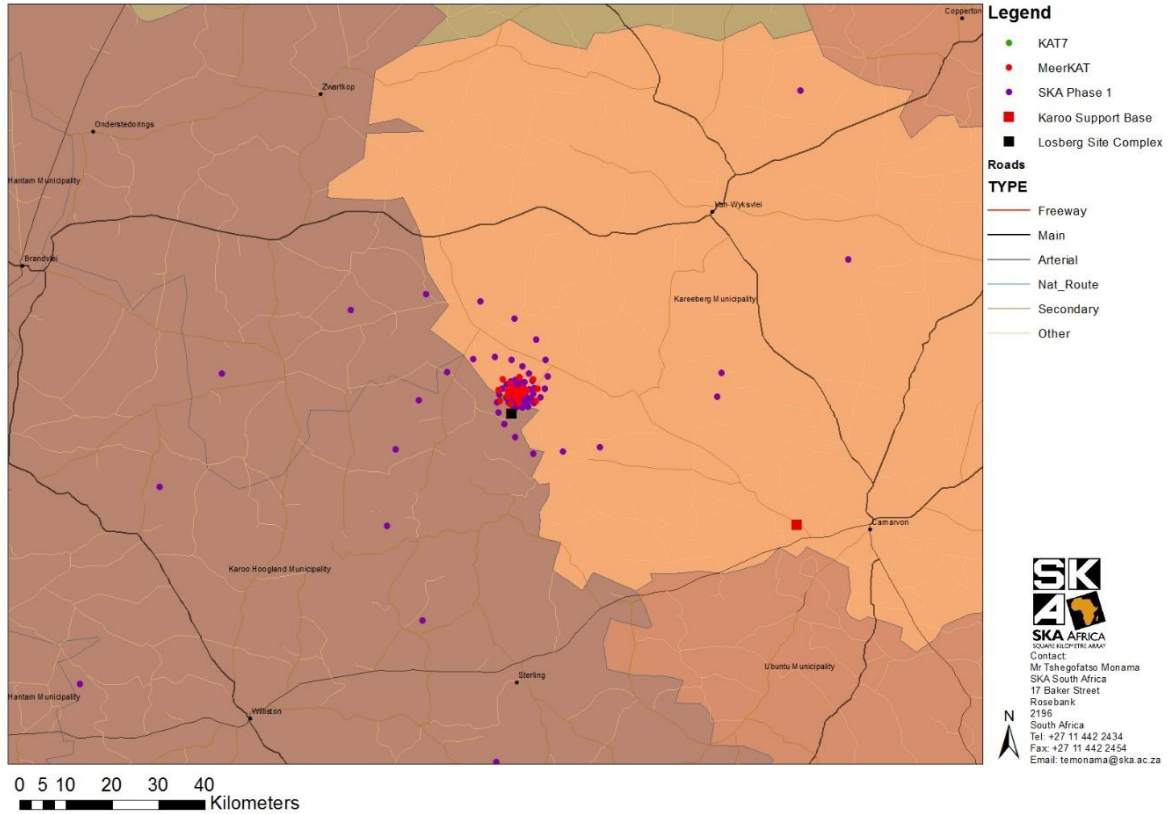
Figure 1.2: SKA1 Latest Configuration (T. Lekalake, 2014)
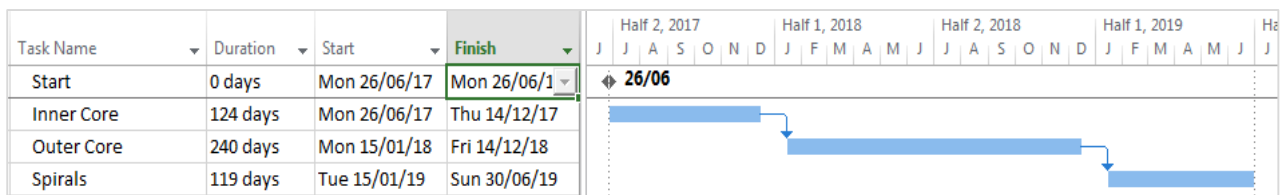
Figure 1.3: Required completion dates

The investigation of feasible construction configurations will not be limited to the construction phases shown in Figure 1.3, but will also explore other alternatives. However, the construction deployment strategy will have to meet these time constraints as well as other determining factors, discussed in Chapter 2. Therefore, with many project interdependencies present the selection of a deployment strategy becomes a hard task for a construction manager, without some form of quantitative measure to select feasible alternatives.

1.3   Problem Description

In CHAPTER 2 an informal SKA project description is included, providing an overview of the various project and construction characteristics that influenced the direction of the research investigation of this study. Therefore the reader is advised to consult CHAPTER 2 if additional clarification on the topics included in this section is required.

Various alternatives for increasing the effectiveness of a construction deployment strategy have been explored by investigating literature and confirming the findings by interviewing experts (see Appendix A). From this investigation three candidate problem areas have been identified, since their improvement would make the greatest contribution to the development of an effective construction deployment strategy for SKA.

Accordingly, the three problem areas are as follows: (1) the *Site Layout* problem (i.e. facility location problem), owing to the large construction site of SKA. Transportation of resources to and from supply facilities (i.e. batch plants, site offices, fabrication yards, various workshops etc.) becomes an important factor to consider in terms of time and cost (Chau, 2004); (2) the *challenge of ensuring high construction productivity*. With the aim being to develop an efficient and cost-effective deployment strategy, it is required to optimize the elements with the most influence on time and cost and to ensure that they are executed effectively (i.e. it may be the improvement of the execution of a basic construction operation that is repeated 190 times); (3) The *Repetitive Project Scheduling* problem, as a consequence to SKA falling within a range of certain types of projects that consist of a repetitive sequence of construction operations. The three problem areas of focus are discussed below in more detail.

The site layout problem

The impact of site transportation on cost was determined to be insignificant, compared to the cost of labour, equipment and material. The transportation cost was estimated based on considering the cost of concrete supply to antenna foundations. When taking an average travel distance and also assuming that one concrete batch plant is sufficient to supply all foundations, it is found that the transportation cost is only 4% of that of the material. However, when the supply of concrete is investigated from a logistics point of view, it becomes clear that the delivery of the volumes required across great distance to various destinations becomes a challenging task in the time frames required. The same can be argued for the supply of all other material on site.

Once the problem is examined from this perspective it is clear that the successful project completion in terms of time is largely dependent on the location of the batch plant and also on other temporary construction facilities on site. The possibility of adding one or more additional

batch plants changes the range of possible solutions to the problem. The solution may have a reduction in time as outcome, which will make the strategy more efficient, but will most probably be more expensive due to the establishment cost on site. Therefore it was deemed necessary to investigate the cost and time implication of various site layout configurations in order to accurately find the most feasible solution.

The challenge of ensuring high construction productivity

The construction on SKA will take place over a large area, at multiple destinations simultaneously. It is important in this case that operations are planned to be executed effectively because when construction commences on site, control and co-ordination will be a major challenge. However, the nature of the construction poses an opportunity where any improvement on the execution of a single operation can lead to a massive positive impact on the total project outcome, since almost all operations are repeated 190 times.

It is suggested to focus on basic activities such as excavations and placing of concrete rather than on small specialised items (Woodward, 1975). The Pareto principle, known as the 80-20 rule, justifies this by stating that a small proportion of the total amount of different items lead to the largest proportion of cost i.e. 20 % of bill leads to 80% of total cost (Thuesen, Jensen & Gottlieb, 2009; Woodward, 1975). For example, the concrete supply operation can be analysed with the purpose of identifying the optimum number of concrete trucks to be deployed.

The repetitive project scheduling problem

Due to the nature of the SKA construction project, it falls within the range of certain types of projects which consist of a repetitive sequence of operations. In such projects specific attention must be paid to ensure that the individual activities are properly synchronised in duration and productivity, if gross delays and misuse of resources are to be avoided (i.e. ensure the uninterrupted utilization of resources) (El-Rayes & Moselhi, 2001). In literature it is said that normal networks such as the critical path method cannot assure requirements of uninterrupted usage of resources (Haplin, 1992; Haris & Ioannou, 1998; Mahdi, 2004; Srisuwanrat, 2009). Accordingly, the SKA project requires that the sequence of work processes, at each of the 190 repetitive units, be synchronised with a suitable scheduling method.

1.4 Research Objectives

The primary goal of this study is to develop a decision support system which can be used by a construction manager to identify a near-optimal deployment strategy from multiple alternatives. Such a decision support system should be able to give a quantitative measure of how the deployment strategy performs in terms of time and cost. The primary goal is broken down into the following objectives:

- Review literature and perform interviews to identify strategies that can be used to solve the challenges faced by the construction of SKA. Include these strategies in an interactive decision support model that can be used to plan an effective construction deployment strategy.

- Formulate and develop an interactive site layout planning (SLP) model that is integrated with the material supply on site. This model will be used to find the most feasible location for temporary construction facilities on site, taking into consideration the travel time, number of similar facilities on site (i.e. multiple site camps), material supply logistics and operational constraints associated with the transportation to antenna foundations.

- Identify a logical sequence of activities and other associated resources required to complete the construction of an antenna foundation.

- Formulate and develop a repetitive project scheduling (RPS) model that is integrated with the SLP model. The purpose of such a model would be to reduce the project duration and maximize the labour resource utilization on site. The model must automatically generate an activity-based network schedule that allows for the repetitive nature of the antenna foundation construction, multiple-activity crew assignment and user-defined labour crew interruptions. In order to do so the schedule must comply with job-logic constraints, resource availability constraints and resource continuity constraints. The user must also be able to interact with the RPS model and make changes to the schedule, for example assigning additional labour crews to an activity for the purpose of reducing the project duration.

- Speculate on possible modes of operation of the model and suggest improvements to be made.

1.5 Scope and Limitations

The scope and limitations have been chosen to define an achievable objective for the study. This study only focuses on the construction deployment planning of antenna foundations. However, interesting and relevant information found in literature and interviews regarding the construction planning of other infrastructure sub-elements, will be mentioned briefly.

It was considered a high priority to formulate both the site layout and repetitive schedule simulation-based framework in such a way that it truly reflects the practical conditions on site. Therefore the models are designed as interactive decision support systems. Such a tool will require the input from a user with experience in site layout planning and construction network scheduling. The SKA site is also subjected to various complicated dependencies and operational constraints such as the geometrical constraints involving the availability of water on site and the location of mountains or water basins. It was not the purpose to develop an optimization model that uses heuristic algorithms to search automatically for the optimum solution while taking into consideration all these project dependencies, although many of the optimization models in this field have implemented this approach. It is rather proposed to produce a model that gives the user control over the proceedings, by providing functionality that allows users to interactively make informed or knowledge-based manipulations of the site's layout and construction schedule. However, such automatic optimization models were investigated, as well as the possibility of integrating such implementations to guide a user in the layout and scheduling task.

Nevertheless, the construction manager can use the model to validate decisions when there is a high level of uncertainty involved in a particular scenario. The model is developed in a generic manner, which will allow users to configure site layouts and schedules relevant to their own project objectives.

1.6 Research Methodology

The research work in this study is organised into six major tasks as shown in Figure 1.4 and is designed to achieve the objectives listed in §1.4. This section also describes the thesis layout and content of each chapter.

Task 1: Literature study

This task entails a literature review on strategies available to solve the problems and challenges identified from the *Investigation of the SKA Project.* The optimization methods and techniques reviewed are applications used by different industries, but especially by the construction industry. From the methods reviewed, the best candidates were selected for further investigation. The research task is accordingly divided into the following subtasks:

1. Review developments in the domain of solving the *Location problem*. This problem is addressed by researchers from various industries such as in supply chain management, Ready Mix Concrete domain and health care services. Special attention is paid to the construction industry where site layout optimization models are developed to determine the optimum location of temporary construction facilities.

2. Review the *Ready Mix Concrete (RMC)* domain to identify methods that can be used to plan for effective concrete delivery on site.

3. Investigate previous research developments in the planning of the supply of materials and the planning of their onsite storage.

4. Investigate the principles of conducting a *Method study* in construction, with the purpose of increasing the production rate of construction operations on site.

5. Review previous developments in the domain of *Repetitive Project Scheduling*. This domain entails scheduling techniques that realise the importance of uninterrupted resource utilization in projects that are subject to a sequence of repetitive activities. From these techniques, a method must be identified that can be effectively integrated with a site layout planning model, to automatically generate the entire project construction schedule.

6. Explore previously developed models in all the major domains of this study, including site layout planning, material supply and repetitive project scheduling.

Task 2: Informal SKA Project description

The goal of this research task is to identify the challenges faced during the construction of 190 antenna foundations over the very large area of SKA. The subjects covered in the review are related to the following:

1. Construction site
2. Influential lessons learned from MeerKAT
3. Interesting alternative deployment strategies
4. Construction sequencing
5. Various concepts that should be considered

It is these project characteristics that need to be considered during the development of a construction deployment strategy. It is also these important characteristics that influenced and determined the research direction of this study.
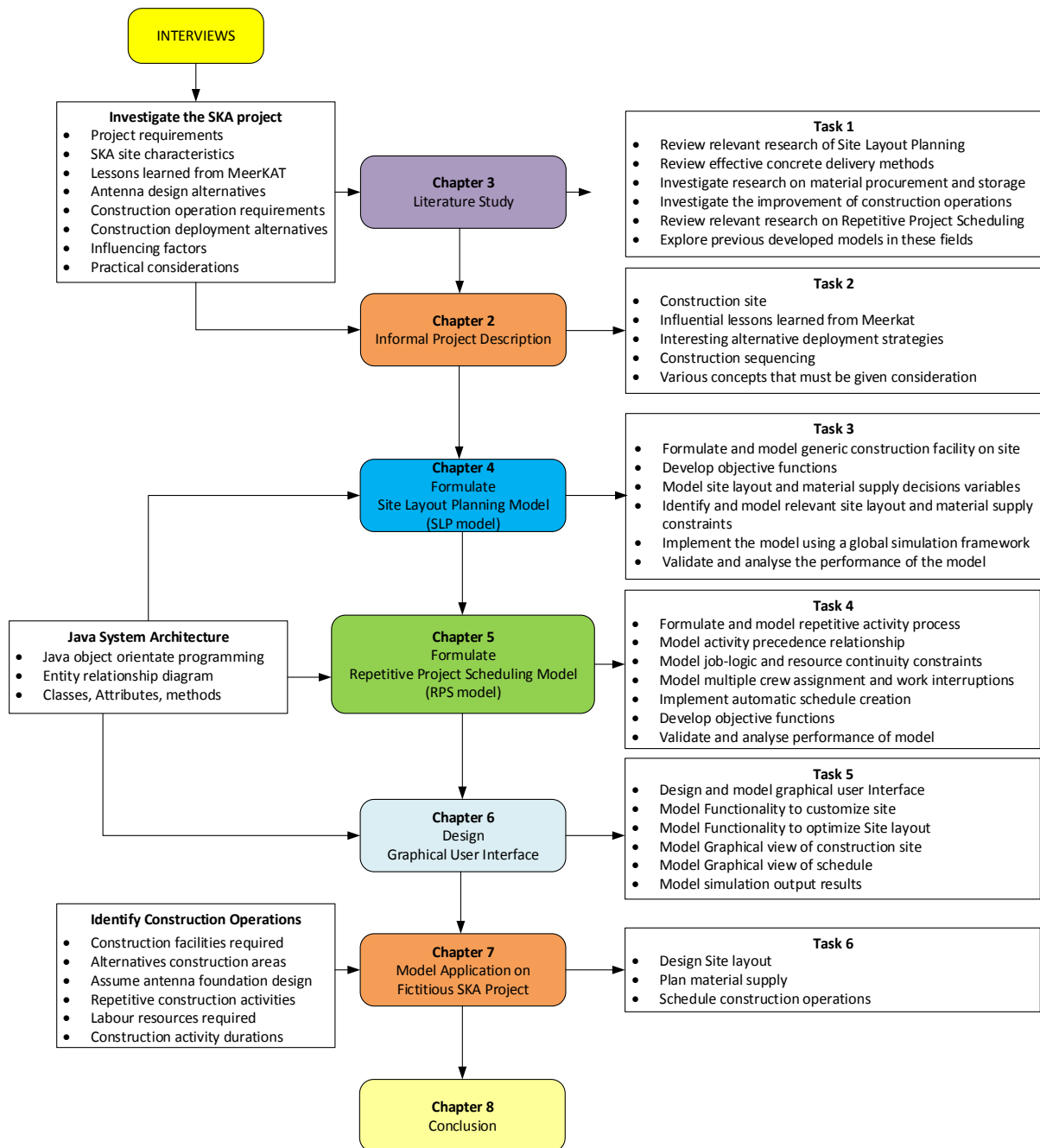
Figure 1.4: Research Methodology and Tasks

Task 3: Site Layout Planning (SLP) Model

The purpose of this task is to formulate and develop a multiobjective interactive site layout planning model that can be used as a decision support tool during the development of the construction deployment strategy. This research task is organised in to the following subtasks:

1. Formulate and model a generic construction facility on site, in order to allow a user to customize the site.

2. Develop objective functions to be used for measuring the effectiveness of a designed layout. The problem has both cost and time objectives, although time is presented in terms of transfer time of resources on site and not project duration.

3. Investigate and model site layout and material supply decision variables.

4. Identify and model relevant site layout and material supply constraints.

5. Model the integration of the site layout and material supply. Thus the model must consider the delivery of a commodity for a specific demand.

6. Implement the model using a global simulation framework. Design an algorithm that simulates the effectiveness of a site's layout upon execution.

7. Validate and analyse the performance of the model to ensure that algorithms execute correctly and accurately measure the site layout.

Task 4: Repetitive Project Scheduling (RPS) Model

The purpose of this research task is to develop a multiobjective repetitive project scheduling model that can be integrated with the SLP model and can automatically generate an entire project construction schedule. The efforts in this task are organised in to the following subtasks:

1. Formulate and model a repetitive activity process. Design the model in such a way that the user is only required to define the activities, their durations, precedence relationship and respective crew assignments of one single repetitive cycle.

2. Model activity precedence relationships.

3. Model job-logic and resource continuity constraints.

4. Model multiple activity crew assignment and crew work interruptions. This will make it possible for a user to assign multiple crews to an activity, so that the work is executed in parallel and also to specify crew work breaks between repetitive units.

5. Implement automatic schedule creation. The model must deliver a schedule for the project with zero crew work interruptions for all the foundations included in the SLP model.

6. Develop objective functions by which the effectiveness of the construction schedule can be measured.

7. Validate and analyse performance of the model.

Task 5: Graphical User Interface (GUI)

The purpose of this task is to design a graphical user interface that has the necessary functionality to allow users to have control over the SLP model by interactively making informed changes to the layout alternatives to produce the optimal site layout from the alternatives. These efforts in this task are organised in to the following subtasks:

1. Design and model a graphical user interface that is integrated with the SLP model and RPS model.
2. Model the functionality to customize a site.
3. Model the functionality to optimize the site layout.
4. Model the graphical view of the construction site, showing the locations of construction facilities and foundations on site in order to communicate visual information.
5. Model a graphical view of the construction schedule in the form of activity production curves in order to provide a graphical display of the schedule to the user.
6. Model quantitative simulation output results which entail the output of the designed objective functions.

Task 6: Model application on Fictitious SKA Project

The purpose of this task is to show an application of the models developed in this study and how it can be used to develop an optimized construction deployment strategy. These efforts in this task are organised in to the following subtasks:

1. Design an optimized site layout for the fictitious SKA project.
2. Design an optimized construction schedule for the repetitive activities.

CHAPTER 2

Informal SKA Project Description

This chapter provides a brief overview of the important project characteristics and construction characteristics that influenced and determined the research direction of this study. The information provided here relate to (1) compensating for SKA phase 2; (2) the antenna platform design; (3) the size of the construction site; (4) lessons learned in the precursory MeerKAT project; (5) possible alternative construction areas; (6) the repetitive activities required at an antenna platform; and (7) planning for the construction deployment strategy.

2.1   Project characteristics

This section discusses the project transition to Phase 2, the design of the antenna foundation platform and the construction site.

2.1.1   Project phases and transitions

The SKA project has been subdivided into various high level phases as illustrated in Figure 2.1. The transitions between phases will overlap, with the next phase starting before the previous phase has been completed. Work will therefore be conducted concurrently as the phases overlap, thus good management and control over the site and construction operations will be essential.

The split of the construction into two phases serves to reduce overall development risk: Phase 1 will serve as baseline for production of key areas of the project before the much larger roll-out of equipment in Phase 2 commences. Phase 2 of SKA will have 2400 dishes over a 180 km distance and a total of 3000 dishes over 3000km (Bolton et al., 2011). The dish positions of Phase 1 are taken to be a subset of Phase 2 positions. Therefore Phase 1 is not an end in itself, but rather a "waypoint" on the way to SKA Phase 2 (Dewdney, November 2010). SKA2 differs from SKA1 in two ways: (1) rate of roll-out of equipment on site will escalate with resulting increase in installation; (2) SKA1 will be utilised for early science work while the construction of SKA2 continues around it (Lekalake, November 2014a).

The decision support model developed to plan the antenna construction deployment for SKA 1 will thus be of even more benefit during the construction of SKA 2 for the planning of the production increase of 3000 foundations.

				SKA High Level Project Phases							
Preparatory Phase (PrepSKA)	Preconstruction Phase			SKA1 Construction			SKA1 Operations				SKA2 Operations
	Stage 1	Stage 2					SKA2 Construction				
				SKA System Engineering Phases							
Concept	Definition	Preliminary Design	Detail Design	Preliminary/Full Production	Site Integration and Testing	Commisioning	Operations and Support				
				Preliminary Design		Detail Design		Preliminary/Full Production	Site Integration and Testing	Commisioning	Operations and Support
Concept	Development			Production (SKA1)			Utilisation (SKA1)		Support (SKA1)	Utilisation (SKA2)	Support (SKA2)
				Development (SKA2)			Production (SKA2)				

SYSTEM LIFE CYCLE STAGES AS DEFINED IN ISO/IEC TR 24748-1 AND USED IN ISO/IEC 15288

Figure 2.1: SKA Project phases

2.1.2 Radio frequency interference (RFI)

There is a RFI policy due to the radio astronomy performed on site. The management of RFI is critical for the successful operation of SKA (Van der Merwe and Cheetham. 2013). This poses a key issue during construction which is not present in most other infrastructure projects. Radio frequency (RF) emissions must be kept to satisfactory level in RFI sensitive areas (Losberg vicinity). Equipment that is sensitive to RF emissions must be protected by shielding them. Possibilities are to place this sensitive equipment in RFI-shielded containers. Another possibility can be to shield the source of RF emissions, like for example an excavated soil screening RFI berm (Nuweberg) was constructed to limit RFI emissions of the Karoo Array Processor Building (KAPB) (Van der Merwe and Cheetham. 2013). Also the building was constructed mostly below ground level allowing the surrounding soil to absorb RFI emissions.

It is however not the objective of the study to solve this operational constraints, as mentioned in §1.5, but to create a model which a construction manager can use while taking into consideration the operational constraints.

2.1.3 Incomplete preliminary design phase

It is necessary to mentioned that at the time of this study the preliminary design had not been completed. Accordingly, the ideal situation would have been to complete the preliminary design before conducting this study. The implication of this is that the deployment strategy will continue to evolve as the design develops further. Therefore the product of this research study must be designed in order to compensate for scope changes and to remain useful in such cases.

Much of the information included in this section was only made available in March 2015. Therefore from the start of this study the research strategy was one of how to manage change. This had a major impact on the development of the product of this study.

2.1.4 Construction site

The construction site for SKA stretches over a very large area (see Figure 1.2), thus causing the dish (i.e. antenna) foundation units to be located at large distances from each another. It is estimated that there will be approximately 560km of farm roads, comprising 150km of new roads in the spirals, 12km of new roads in the core, and 398km of existing farm roads in the spirals (Lekalake, November 2014b).

Located adjacent to the spiral arms are farms which are suitable as candidate destinations for the sourcing of material (i.e. borrow pits), which will supply material for the access roads, earth berms and the antenna platforms. There are also farms situated closer to the core which will serve as candidate destinations for accommodating contractors and their personnel.

2.1.5 Lessons learned from MeerKAT

Figure 2.4 shows pictures of the MeerKAT antenna foundations. The lessons learnt during the construction of MeerKAT antenna foundations included a list of factors related to the size, implementation, installation etc. For example; the thickness of the platform can be reduced; there is no need to galvanise the entire length of holding-down bolt since 70 % of the bolt length is cast within concrete; a solution to performing x-ray testing on all the welds might be to x-ray a few welds and perform dye penetration tests[1] on the remainder of the welds. All these items gave reason to consider an optimised MeerKAT design approach and two further precast design solutions. The new design of the Antenna Foundation subelement is still in the preliminary phase.

All lessons learnt are very important to consider. However, the most important factor which is closely associated with this study, is that the supply of concrete to the antenna foundations was too slow. This was probably the main reason for the consideration of a precast option.

2.2 Construction characteristics

This section provides information regarding the construction and the major cost drivers.

2.2.1 Alternative construction areas

In terms of defining the construction deployment methodology, INFRA-SA proposed to either use a general approach, involving a single construction area (i.e. centralized option) with

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[1] low-cost inspection method used to locate surface-breaking defects in all non-porous materials (metals, plastics, or ceramics).

defined teams; or to divide the site into a combination of various areas (i.e. decentralized option), with the aim of developing the most cost-effective and efficient strategy. In the decentralized option, each area would have its own teams and its own site establishment.

Accordingly, a trade-off study should be performed to determine which is more feasible: a single centralised construction camp where all activities are co-ordinated, including all 190 antennas; or to have various decentralised construction areas where the activities are co-ordinated from the core construction area. In the second alternative, however the optimum number of antenna's included in each construction area must be determined (i.e. 100 in the core and 30 in each of the 3 spirals or 70 in the core and 40 in each of the 3 spirals etc.). There are many factors influencing such a decision, for example the fact that 61 % of the 190 antenna foundations are located in the core. It is not the objective of this study to perform such a trade-off, but to develop a prototype decision support software that can aid managers in their task.

2.2.2 Factors influencing the selection of a deployment methodology

The selection of a deployment methodology is dependent on multiple factors as shown in Figure 2.2. Most of these factors listed are major cost drivers and therefore a deployment strategy must be selected that delivers an optimum balance between these factors (Lekalake, 2015).
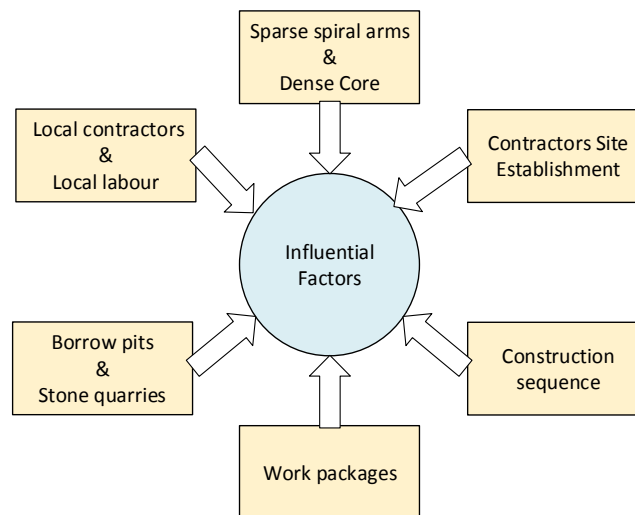
Figure 2.2: Influential factors in the selection of a deployment strategy
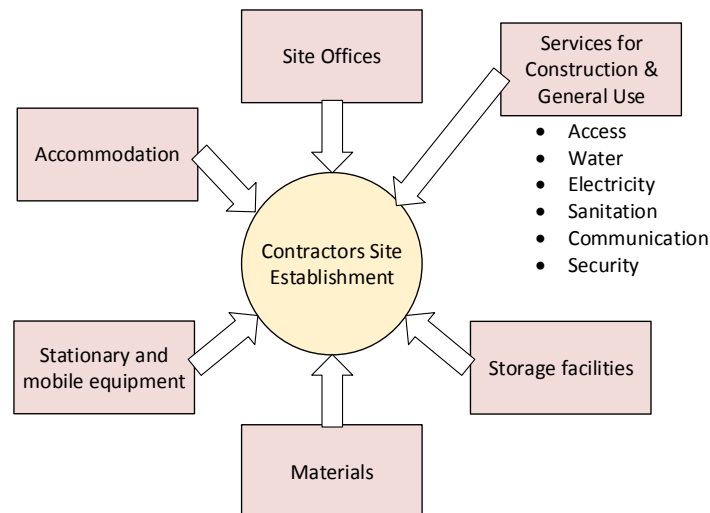
Figure 2.3: Items included in the contractor's site establishment

An experienced construction manager can qualitatively assess the various alternatives with respect to how they perform in terms of the factors listed above. For example the advantages of having a single-centralized construction area include a lower overhead cost on site along with better control over supplying material from a single point. These advantages must however be weighed against the disadvantages which include a greater travel distances on site and challenges in getting material (i.e. concrete) to destinations in an acceptable condition. These disadvantages might be compensated for with the advantages of a decentralized construction area, which pose additional benefits such as the deployment of construction from smaller manageable zones.

It is clear that both strategies have their own advantages and disadvantages. However, it is necessary that the trade-off study include a quantitative analysis in order to accurately identify the most feasible solution with respect to multiple project objectives (i.e. time, cost and quality). The importance of such an assessment becomes even more vital when the planning of the construction deployment of SKA2 is considered. It would be ideal to integrate the expert judgement of a construction manager with a model that measures decisions quantitatively.

2.2.3   Repetitive antenna foundation construction activities

The critical construction activities required to construct a MeerKAT antenna foundation were identified based on interviews with the full time construction manager on the MeerKAT project (Dawie Le Roux, see Appendix A). The activities and their related information are shown in Table 2.1. The highlighted super script letters visible in Table 2.1 are associated with the points below:

1. In MeerKAT it was found to be much more effective to pre-fabricate the steel cages for piles at a fabrication yard on site and to transport the steel cages to the foundations.

This alternative increases the productivity and also reduces the wastage of steel off-cuts on site.

2. It takes one day to cast the concrete of foundation piles but there is a 3 day curing period before crew 4 can start with the excavation of the foundation platform.

3. The foreman will oversee all the construction activities performed by the various crews.

To prevent the activities involved with the construction of the piles, from advancing far ahead of the rest of the construction, the crews (crew 1 and 2) assigned to those activities may be reassigned to different activities once they have created enough work for the other crews to catch up. For example, the two concreting activities can be completed by the same crew.

Table 2.1: MeerKAT antenna construction activities

Crew	Activity	Duration (Days)	Labour requirements	Equipment
1	8 Steel reinforcement cages[1]	1	6 labour	Steel fabrication plant
2	Drill foundation piles	1	4 labour +1 gang boss+ 2 operators	Piling rig + Digger loader+ dumper truck Crane
3	Insert steel cages in piles + cast concrete	1, (3 lag[2])	3 labour+1 gang boss+ 1 crane operator+ 1 foreman[3] + 1 surveyor	Crane+ Steel truck with crane
4	Excavate platform	4	4 labour+ +2 operator+1 surveyor	Digger loader + Dumper truck
5	Earthing	1	2 electricians	_
6	Blinding layer	1	8 labour + gang boss	_
6	Steel Reinforcement	3	8 labour + gang boss	Steel truck with crane
6	Install and remove Shutters	1	8 labour + gang boss	Shutters
7	Concrete	1, (3 lag[2])	3 labour+ gang boss or Team 3[4]	Direct charge
8	Back fill	1	4 labour + 2 operator	Digger loader + Dumper truck

Note: The red letters in the Table refers to the numbered list above the Table.

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2.3 Construction deployment considerations

This section provides information regarding the planning of a construction deployment strategy and typically some of the factors that must be addressed.

2.3.1 Sequencing the construction of antenna foundations

It is essential that the representation of the sequence of operations within the execution strategy be clearly defined. Construction planners often express the coordination of planned schedules based on highly conceptual space terms such as: North, South, East and West. Take for example a construction planner conveying the execution of Ground Floor Steel Columns activity to begin from the East and progressing towards the West. The execution plan of such an activity is left to the workmen on the site (Mallasi, 2006). Due to this there may be work interruptions between construction activities, especially in large complex construction projects, where two activities have the same space requirement.

2.3.2 The importance of resource transfer time on site

Labour and equipment cost is very high. Therefore, to have idle resources (not performing work) because they are traveling over long distances to work destinations is undesirable. It would be ideal to have the expenditure associated with this time resource spent in idle, so that it can be used in a trade-off study. Such a trade-off study may entail investigating the feasibility of adding additional facilities on site with the aim of reducing the average transfer time of resources between work destinations. The direct result of such a reduction in the transfer time on site is an increase in the productivity of the associated operations.

It is also possible to solve an unacceptable transfer time on site from a logistics point of view. In such a case the number of trucks assigned to handle material can be increased and as a consequence the delivery/transfer time will be decreased. However, when working in the dense inner core area of SKA, any redundancy in the number of operating trucks may cause waiting queues on site. This is especially the scenario that will arise during the mass haul operation, when haul trucks load and offload material during the road construction. A different approach could be to increase the carrying volume of the trucks, which will require that less deliveries be made and therefore resulting in reduced transfer time. However, such a strategy may have a higher vehicle procurement cost associated with it.

2.3.3 Selecting the optimum number of labour teams

This is probably the factor that has the greatest influence on project duration. The critical activities, for example the ones that take the longest, can be reduced in duration by assigning additional labour teams to complete the work simultaneously. However, such assignments

must be carefully synchronized across the construction network to avoid the misuse of resources.

2.3.4 Synchronizing the production rates of operations

This is one of the most important aspects that needs to be maintained in the development of the deployment strategy. The production rates of operations must be balanced in such a way as to remove idle time of resources. This synchronization should not only be applied to operations of the same type (i.e. between construction activities), but across the entire construction network (i.e. "batch plant capacity" and "concreting crew productivity"). For example the rate at which the batch plant can supply concrete should be synchronized with the concreting team's production rate, to ensure that the team has concrete available on time. The different production rates of construction activities should also be scheduled to ensure that labour teams do not interrupt each other (i.e. 'drilling of piles" and "concreting of piles"). Accordingly, every operation must be scheduled to ensure that the project is completed on time.

2.3.5 Slow concrete supply on site

The reason for slow concrete supply on the SKA site can be explained. In order to do so it is necessary to explain some of the logistics involved in procuring concrete at antenna foundations. The SKA site is located too far from any Ready Mix Concrete suppliers and therefore concrete will be supplied by an on-site batch plant. If it is assumed that the MeerKAT foundation design is used, the following applies: Each foundation is required to be serviced by a batch plant twice; once for the concrete casting of 6x6m deep foundation piles ($36m^2$) and a second time a few days later for the concrete casting of the foundation platform ($36m^2$). Refer to Figure 2.4 to see photos of the construction progress on a foundation. Accordingly, there are 190 foundations that need to be supplied with roughly $72m^3$ of concrete each. This results in a total number of 380 delivery points which must be completed over the project duration. If the available time is considered, a batch plant will need to service 2 foundations per day for roughly half of the project duration in order to complete all of the foundations at the required dates of dish access (see Figure 1.3). In order to deliver this daily requirement, 12 ready mix trucks must be dispatched each day.

This assumption however ignores the fact that certain destinations might be too far away from a concrete source on site, for example in the case where it exceeds the cold-joint[2] time constraint of concrete. In these cases the batch plant will have to move and an additional re-establishment cost will apply. It is a possibility to add concrete additive materials to reduce the curing rate of the concrete, so that it can be transported over greater distances. However, the concrete will then become more expensive on site.

Furthermore, there is roughly a 4-5 hour window period on site to cast concrete (e.g. in the morning and late afternoon), since the weather conditions are too hot the rest of the day (assuming the worst case during summer and spring). Moreover, the efficiency at which a batch plant can dispatch a ready mix truck is dependent on many factors. However, to simplify the calculation, it is assumed that the batch plant will operate at a full capacity of 4 trucks/ hour, dispatching a ready-mix truck every 15 minutes. It will then take 3 hrs at full capacity to meet the daily requirement. It is highly unlikely that a truck will be ready every 15 minutes if the turnaround time (i.e. loading time, travel time, unloading time and return time) on SKA is considered.

Therefore if all these factors are taken into consideration it is clear that the supply of concrete requires proper planning and the same can be argued for the handling of other materials on the SKA site.

2.3.6 Farm road construction consideration

The construction of the farm roads of SKA is mostly dependant on the distance at which the borrow pits are located from where the road is being constructed. The greater this distance the longer construction takes, because of the longer turnaround time of haul trucks. Since travel distance is the constricting factor on the road construction progress, more trucks will be required when roads are constructed in the spiral arms.

The first alternative during the mass haul operation could be to completely utilize one borrow pit before sourcing material from the next feasible location. For example, this strategy will require only one excavator and maybe 10 dump trucks. A second alternative would be to use multiple borrow pits to reduce the time wasted by waiting in queues during the loading of dump trucks. However, such a strategy will require the deployment of an excavator at each of the

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[2] Cold joints are formed between two batches of concrete where the delivery and placement of the second batch have been delayed and the initial placed and compacted concrete has started to set

borrowing sites, assisted by maybe 5 dump trucks each. Once again the balancing of the operating cycle times of units in the system is crucial.

It is estimated that one can construct roughly 500m of road a day on SKA. The construction can be performed by two teams:

1. Load and haul team, together with a team that follows behind, flattening and fixing the surface.
2. Scraper that mixes the material with water, sprayed by a water truck and then a roller machine that follows to compact the surface.

Note that it takes half a minute to unload a dump truck and half an hour to fill a water truck.

2.4 Concluding remarks

The needs to be considered in the model, identified from the various topics discussed in this section, can be summarised as follows:

- Plan for the production increase in SKA2
- Compensate for the incomplete preliminary design of antenna platforms
- Manage large travel distances posed by the large construction site
- Identify locations amongst multiple candidate positions for temporary construction facilities
- Manage the challenge of material handling on site (i.e. slow concrete supply)
- Identify best option amongst multiple possibilities of organising construction areas
- Design quantitative measures of the various factors influencing the deployment strategy
- Integrate expert qualitative judgement with quantitative measure.

Photo 1: MeerKAT Antenna Foundation Piles

Photo 2: Earthing and Lightning Protection Scheme

Photo 3: Pile Cap Reinforcement

Photo 4: Pile Cap Reinforcement incorporating Bolt Assembly Cage

Photo 5: Completed MeerKAT Foundation after striping of formwork

Photo 7: MeerKAT Antenna on a Foundation

Figure 2.4: MeerKAT antenna foundation photos

CHAPTER 3

LITERATURE REVIEW

This chapter contains a review of the literature on topics related to: (1) the design of a Site Layout Planning (SLP) model that can be used as a decision support tool for managers to decide where temporary construction facilities must be located on site; (2) the theory of conducting a construction *Work Study* on construction operations in order to increase system productivity; and (3) the development of a network schedule to ensure uninterrupted resource utilization for projects with a sequence of repetitive operations. Figure 3.1 summarises the layout of the chapter and also the literature review approach followed in order to provide an optimized deployment strategy for SKA-INFRA. The chapter identifies suitable methods, techniques and models that can be used to overcome the challenges experienced during the SKA construction.
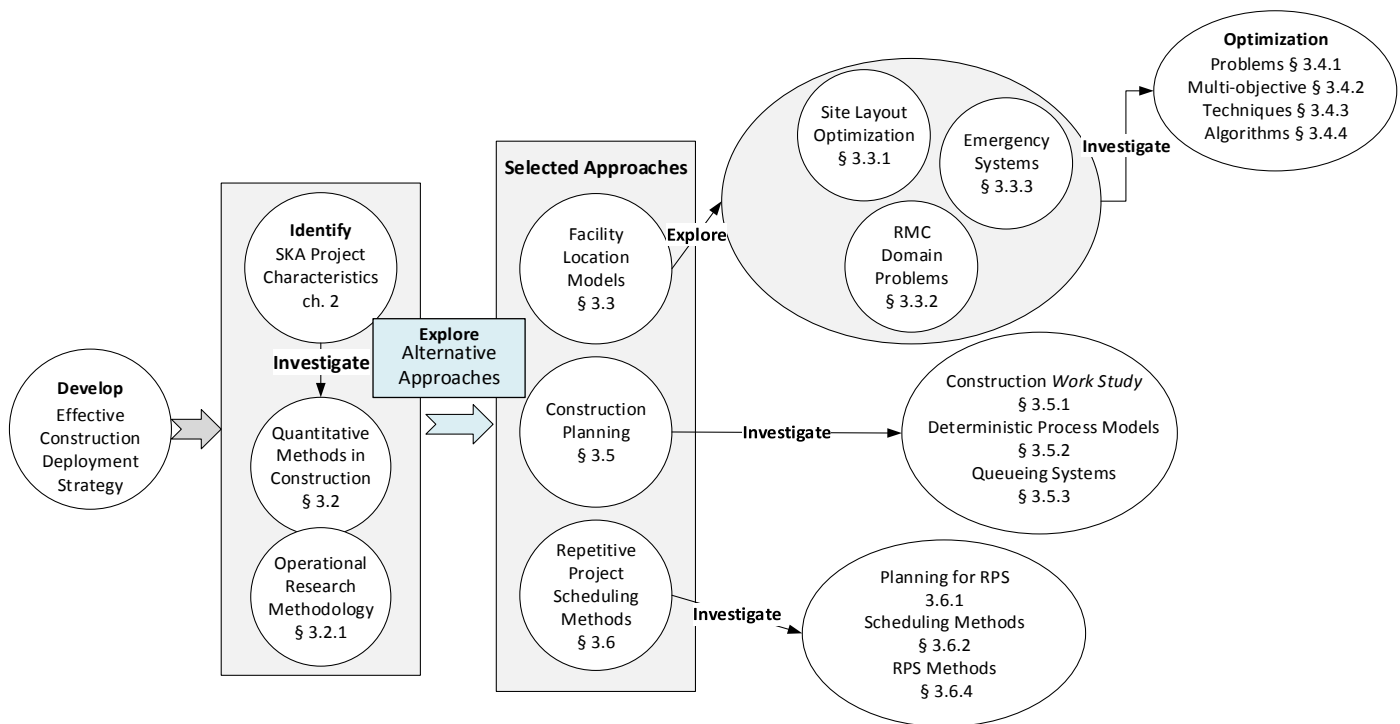
Figure 3.1: Literature review layout

3.1   Introduction

For the process of developing an optimized deployment strategy a review is performed of quantitative methods used as decision support tools. The methods which will be investigated and applied in this study are of quantitative nature and include computational methods, mathematical analysis and model formulation. Many of these techniques and methods are included in the domain of operations research (OR). Other industries such as the

manufacturing or process industries have developed these subjects. However, these methods can also be applied to seek solutions in the construction industry. Methods such as these fall within the general subject area of management sciences. In this section attention is paid to various models developed in industry in order to overcome challenges also identified on SKA. This chapter addresses the challenges identified in §1.3 and discusses the relevant research investigated to help manage and overcome these challenges. The literature review performed in this chapter is done according to the structure laid out in Figure 3.1.

3.2   Quantitative Methods

3.2.1   Operational research (OR)

The term OR was coined in the 1940s to include all modelling related to military operations. It has since come to mean models that represent the behaviour of systems by means of numerical equations and constraints, to which mathematical techniques are applied to find a solution (Tommelein, Levitt & Hayes-Roth, 1992b).

In earlier years operational research in the construction industry was mainly confined to network-planning methods. However, in later years operations research tools and techniques have been applied in the construction industry to optimize its operations.

Essential features of OR

The description of OR listed below is very brief. However, it lists the essential features of OR and describes the logic behind the approach that is used in this study (Woodward, 1975):

(1) A problem area exists in which the objective is to find the optimum solution. The objective function may be to maximize profit or to minimize cost or time. In this study the objective has been defined in section §1.4.

(2) A model is used to represent the system being studied. The model can be of many forms and types. This study will make use of a site layout planning model (CHAPTER 4) and also a network scheduling model (CHAPTER 5).

The above two features are the main characteristics of OR but it also entails the essential steps that are common to management sciences techniques. They are as follows:

(3) Definition of a problem area, which is described for this study in §1.3: As has been mentioned previously, to avoid a solution from becoming unobtainable. It is important to not too closely define and isolate a problem so that it causes sub optimization. For example, it might be decided to optimize the concrete handling methods on a large site. Then it must be ensured that the implementation of the optimal answer for concrete handling on site does not affect other operations so that the overall result is a

deterioration of the system. This is an important aspect that will be considered during the optimization of the construction operations in this study.

(4) Collection of information: The accuracy of data on the problem determines the accuracy of the solution. Therefore data is required that is adequate in terms of both quantity and quality.

(5) Testing of solution: Test the solution on the model which represents the system and, very important, test under actual working conditions. During testing it is important to determine (1) situations where the model does not truly represent the system and (2) factors thought not to be important at first, but which in fact are.

(6) Implementation: Once all other steps have been completed, make sure through a formal review that the system continues to operate as expected. Certain changes in the system may occur with time, leading to changes in the optimal solution.

3.2.2   Optimization models relevant to this study

The use of models is a common feature of management science techniques to address problems. Models are used firstly to understand how the system works and thereafter experiments are carried out on them. This is an advantage, since it does not have the cost or consequences of experiments on full scale projects. Models can be categorised to be descriptive, quantitative, interactive or dynamic (Woodward & Woodward, 1975). For example in this study models will be used to evaluate different site configurations, to plan and analyse construction operations and to design a repetitive project construction network schedule.

The model developed in this study will be of a quantitative dynamic nature and will integrate a site layout planning model, a deterministic process model (representing the flow of dynamic entities (i.e. trucks) on site) and a repetitive project network scheduling model.

Different types of optimizations models have been developed in the construction and engineering management field in order to aid managers, in the form of a support tool, in making better decisions or to validate them when a high level of uncertainty is present. These models utilize various kinds of algorithms to seek optimal solutions to the optimization problem in projects with multiple objectives.

Figure 3.2 shows the research domain areas investigated and how they are mapped on top of one another to show their integration. Figure 3.2 is then imposed on Figure 3.3, which shows a list of the various models reviewed in these domain areas and gives an indication on how these models and their integration can be arranged to indicate the bigger picture and the research of this study.
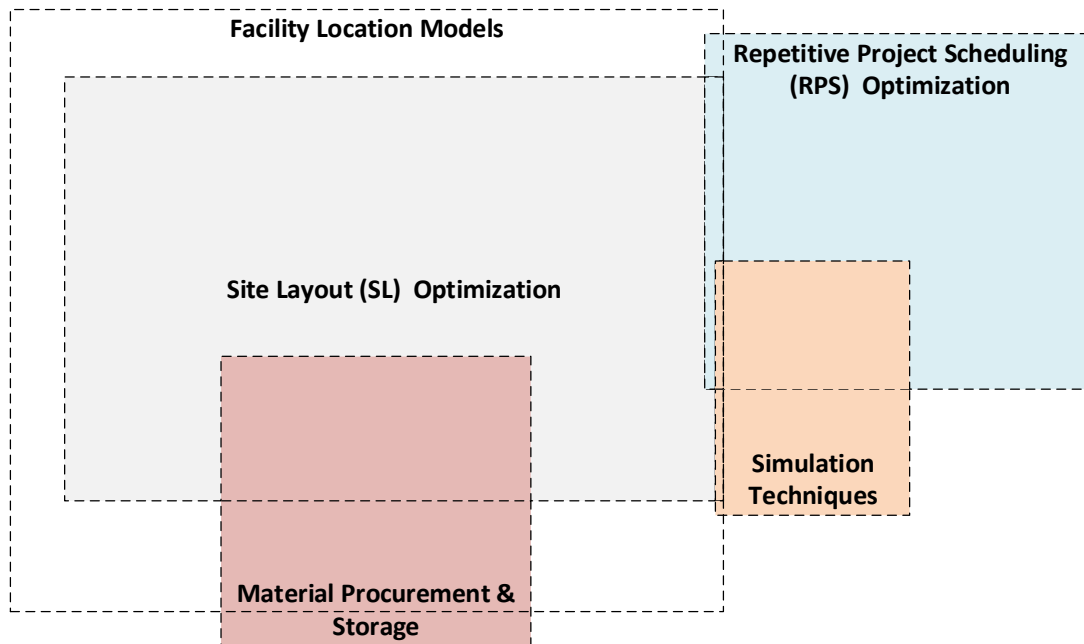
Figure 3.2: Previous research domain areas investigated

The previous research developments reviewed included:

1) site layout optimization models which seek the optimum solution to maximize productivity, safety, control over material procurement, minimize cost, travel time and activity interference on a construction site (Tommelein, Levitt & Hayes-Roth, 1992a), (Tommelein & Zouein, 1993), (El-Rayes & Said, 2009);

2) ambulance location and relocation models that are used to find the optimum location to maximize coverage (Brotcorne, Laporte & Semet, 2003:451);

3) optimization models in the ready mix concrete (RMC) domain, used for finding plant locations, optimizing batch plant facility equipment in order to maximize production, minimize material flow distances (Maghrebi, Waller & Sammut, 2013), (Maghrebi, Travis Waller & Sammut, 2014);

4) simulation-based deterministic process models used for optimizing construction operation, in order to increase the productivity of the system, i.e. an earthmoving mass haul operation is optimized to increase the volume of material moved (Cho, Hong & Hyun, 2013), (Haplin, 1992);

5) space management models that optimize the space utilization, considering the construction schedule over the project (Zouein & Tommelein, 1999), (Zouein & Tommelein, 2001:116);

6) repetitive activity scheduling models to ensure uninterrupted utilization of resources (Harris & Loannou, 1998; Mahdi, 2004).

The application, and more specifically the formulation and implementation of the models listed above, included the domain knowledge on which this study is focused. Therefore, throughout this research reference will be made to these topics. The first topic that will be discussed is plant/facility location models. As will be mentioned later these types of models implement different optimization techniques which utilize different optimization algorithms. Therefore, following the discussion on plant location models, a section on multiobjective problem solving will be covered, (see §3.4.2) followed by a review on the different optimization techniques frequently encountered in the investigation (see §3.4.3). The section on optimization will also be relevant when the network planning models regarding the scheduling of projects with repetitive activities are considered. Listed under facility location models is a discussion on the *Transportation Problem*. This problem is discussed here since the objective function of these problems are to minimize the total transportation cost of deliveries, and is therefore related to the models discussed in §3.3.
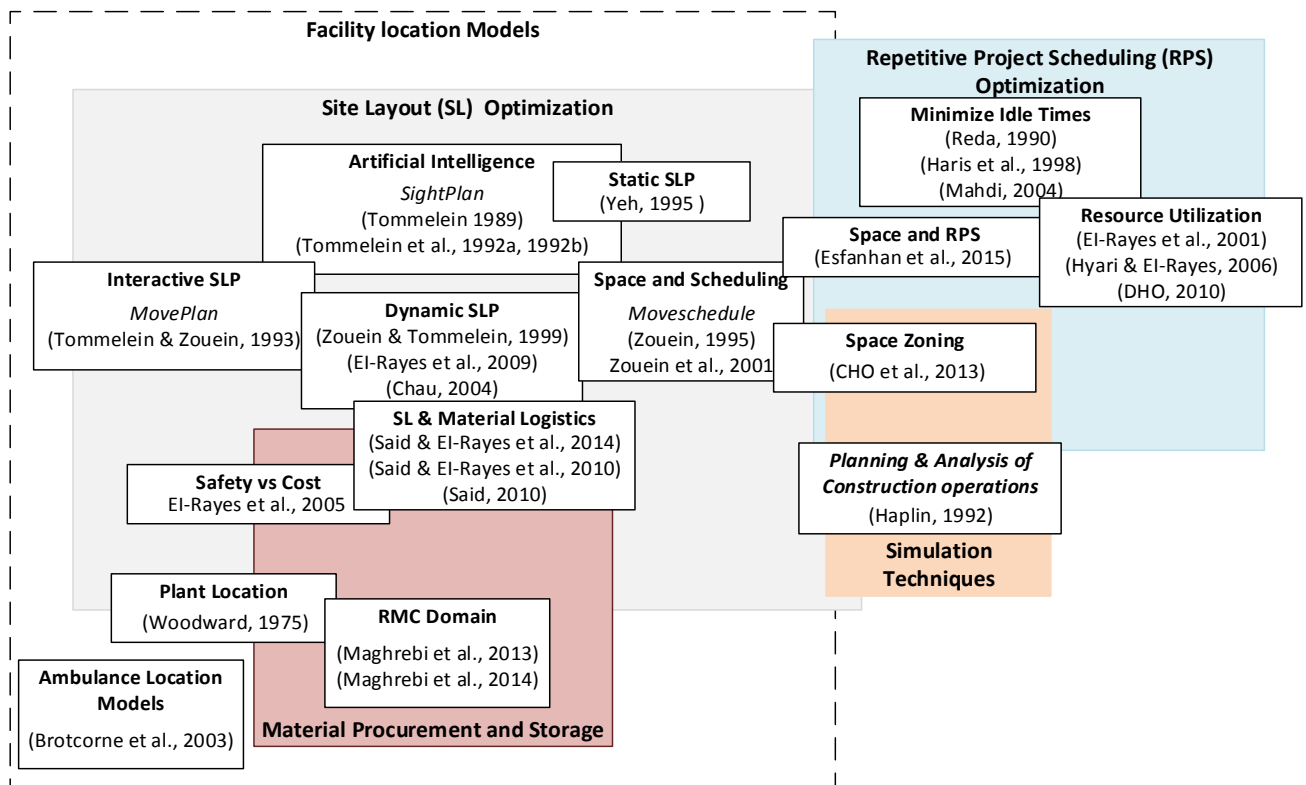
Figure 3.3: Investigated research developments related to this study

3.3 Facility Location Models

Under this concept many different models with different objectives have been developed and implemented in industry and are subsequently discussed in this section. The problem areas for which they have been used for and which are similar to this study include site layout planning, ready mix concrete (RMC) supply problems, ambulance location and relocation models, and supply chain management. The first to be explained, and also the main focus of

this section, will be the planning of construction site layouts. This domain has been identified for review since some of the identified challenges encountered on SKA can be managed by means of such optimization models. The information included in this section contributed to the development of the Site Layout Planning (SLP) model in this study.

3.3.1 Site layout planning models

Many site optimization models have been developed in the construction industry to achieve different objectives (see Figure 3.3). Managers use these models as computer-aided decision support systems in this industry. These models utilize different optimization techniques and algorithms to find optimal solutions, which will be covered in §3.4.

Planning site layouts entails the identification of the locations of facilities that are temporarily needed to support construction operations on a project but do not form part of the finished structure (Tommelein, 1989). Temporary facilities may include storage areas of material and equipment, stockpiles of excavated material, site offices, fabrication shops, and batch plants (Yeh, 1995). The allocation of space to such facilities is a routine task for many site engineers and project managers. Space allocation is important, since it is obvious that the layout of the site affects travel time, activity interference and productivity. The impact of good layout practices to economise on money and time becomes more obvious on larger projects (Easa & Hossain, 2008). In regard to this it estimated that transportation costs account for 10-20% of construction costs (Irizarry, Karan & Jalaei, 2013). A proper site layout can lead to (1) reducing material handling cost; (2) minimizing travel times of labour, material, and equipment; on site (3) improving construction productivity; and (4) promoting construction safety and quality (Tommelein, 1992).

Practitioner's Attitude to Problem

Although site layout has proved to have a major role in planning, it has received little attention due to the complex nature of the problem (Calis & Yuksel, 2010), which is discussed in more detail in section §3.4.1. Also owing to the owner's lack of knowledge and experience in construction, most owners are reluctant to spend money on the integration of the temporary facilities and permanent facilities. Normally designers have a "leave it to the field" attitude towards site layout because such coordination will increase engineering labour-hours. The cost of site planning is typically charged to project overheads and is not treated as a reimbursable item or direct cost (Cheng & O'Connor, 1996).

Nevertheless, site layout planning is a task that has an interactive relationship with other preplanning tasks such as schedule development, selection of construction methods,

procurement planning, workforce planning, material planning, equipment planning, and financial analysis. Therefore it is a task that a construction manager must plan.

Previous developments and Implementation

In earlier years the most popular aids for studying layout were physical models, such as cut-out templates and other types of modelling blocks that people can move around to study space needs and assembly sequences (Tommelein et al., 1992). In later years physical models were replaced by computerized product models that only require the appropriate inputs to generate a site layout.

Researchers have implemented various techniques to optimize the site layout. Some use artificial intelligence (AI) in the form of a knowledge-based system; others try to create a user-interactive component to the proceeding of planning a site layout. Many strive for an automated approach by implementing optimization techniques, such as mathematics and heuristics, with the aim of improving the search for the best allocation of resources on a construction site. These algorithms are sophisticated search frameworks implemented to find either an exact or optimal solution amongst an entire set of solutions. The different algorithms available, specifically those that have been encountered the most, are discussed in §3.4.3. However, existing site layout models can be classified into two main categories, namely static and dynamic, and will be discussed next.

Static Models

Static site layout models produce a single site layout with static locations for all temporary facilities in the project (El-Rayes et al. 2009). The static locations of these facilities do not change over the project duration.

Tommelein (1989) developed "SightPlan", an artificial intelligence (AI) model, often termed knowledge-based systems, that mimics the layout process that construction mangers follow when implementing domain knowledge and heuristics they apply in this process. SightPlan lays out temporary facilities represented by rectangles on a construction site, represented by a two-dimensional space. The formulation of SightPlan was modelled on two case studies of which one entailed deciding on the layout of the long term laydown areas for approximately 25 major contractors. For a full description of the expert layout strategy, refer to (Tommelein, 1989). It was learned from the study that it is feasible for a computer program to mimic the procedure taken by a manager for laying out a construction site.

Moreover, since the early 1970s, several researchers have utilized various heuristics or mathematical optimization techniques to solve the static site layout planning (Elbeltagi, Hegazy, Hosny & Eldosouky, 2001). Yeh (1995) formulated the problem as a combinatorial

optimization problem and used a heuristic method to find the optimal static arrangement of temporary facilities on site. Another site layout planning model, developed by El-Rayes et al. (2005) is capable of simultaneously maximizing construction safety and minimizing the travel cost of resources on site.

It is important to note that the assumption regarding the site layout situation remaining static, is to simplify the problem. In this case the cost for re-establishment and transportation does not change over time (Chau, 2004). Thus static site layout models do not consider the dynamic changes in site space requirements and availability on site.

Dynamic Models

Most construction projects have a complicated production process which generally consists of three main phases: excavation-foundation-substructures work, superstructure work and fitting-out work. This adds to the complexity of the layout, since the site layout will change accordingly to meet the changing demand for materials (Ma, Shen & Zhang, 2005).

Dynamic models are more challenging since they include the relocation of temporary facilities on site over the different construction stages and as a consequence require more sophisticated algorithms to solve. Dynamic layout modelling requires identifying and updating the positions of all temporary construction facilities that are feasible to move, such as offices, lay down areas and workshops over the entire project duration. However, it is important to note that it is not feasible to move certain stationary facilities, such as batch plants and cranes, due to their large establishment cost and therefore their locations are kept static. Many layout changes are direct results of the construction schedule (Tommelein & Zouein, 1993).

Researchers have noticed the construction layout's dependency on the construction schedule and have therefore integrated the layout problem and project scheduling (Zouein & Tommelein, 2001). Dynamic layout considers the changing of space requirements on a construction site and generates a sequence of layouts for each stage in a chronological order, starting from the first stage. The difference in capabilities between static and dynamic models plays a large role on congested sites with limited space.

Model integrating site layout and schedule

Traditional tools for project management do not provide a means to explicitly represent space needs and availability. Researchers have realized the importance of space constraints and have therefore investigated the integration of schedule and layout (Elbeltagi et al. 2001). Tommelein and Zouein (1993) developed *MovePlan* to support an interactive dynamic site layout planning process which considers the resource space needs. MovePlan does so by using the activity schedule data such as the resources required to perform activities and their

dimensions. Zouein (1995) developed *Moveschedule*, an extension to MovePlan, which seeks to reduce the impact of activity space conflicts by adjusting the construction schedule. Similar to traditional resource allocation, these models tried to modify the schedule at various intervals so that the site space is not over-allocated (Zouein & Tommelein, 1999).

Models integrating site layout and material planning

On the construction site it is important to properly plan for the procurement and storage of material in order to avoid the negative impacts of material shortage or excessive material inventory on-site (Said, 2010), (Said & El-Rayes, 2014). Deficiencies in the supply and flow of construction material are often cited as major causes of productivity degradation and financial losses (Thomas, Riley & Messner, 2005). A number of studies have been conducted to develop effective site layout models and to improve site layout planning in construction projects by simultaneously integrating and optimizing the critical planning decisions of material procurement and material storage on construction site. (El-Rayes & Khalafallah, 2005b), (El-Rayes & Said, 2009). The model developed by Said and El-Rayes (2010) is utilized to minimize ordering and financial cost.

It is also necessary to consider the construction supply chain itself, to ensure the delivery of material. The main objective of logistics analysis is to minimize the combination of vehicles, hours or miles required to deliver the product (Ma, Shen & Zhang, 2005). Ma et al. (2005) propose the integrated management of the supply chain and the site production, by taking advantage of integrating building information modelling (BIM) and GIS into a unique system, which enables keeping track of supply chain status and providing warning signals to ensure the delivery of materials.

User Interactive planning vs Black box planning systems

Most models utilizing mathematical and heuristic optimization algorithms are implemented as black-box systems which follow procedures that are incomprehensible or questionable to users (Tommelein et al., 1992). It has also been noted that computer-based design algorithms do not always capture the qualitative and intelligence aspects of layout design and therefore struggle to replace human judgement and experience (Tompkins, White, Bozer & Tanchoco, 2010). More importantly, when users find results different from what they expect, it is difficult to alter the model. Moreover, people are reluctant to take responsibility for an outcome over which they have no authority. Therefore, if one is held responsible for a model's results, one should also have control over the proceedings, even when this means that less-optimal models are preferred.

It is often also easy for experts to visually inspect layout alternatives and judge its acceptability or otherwise. However, computerized generations of alternative layouts could provide the

support for a construction manager by addressing some of the complex problem dynamics (Ahmad et al., 2008). Therefore, a system that combines automated algorithms and allows the user to make knowledge-based interventions will significantly enhance the acceptability of the solution.

3.3.2   Ready mix concrete domain models

The construction site of SKA is somewhat different to that of conventional construction projects, due to the repetitive nature of the construction operations and the large size of the construction site. Therefore the facility location problem is investigated in domains which experience similar challenges, such as the Ready Mix Concrete (RMC) industry and the planning of emergency systems.

In the RMC domain it is one of the objectives to search for a location of a supply depot, and then to determine the most suitable capacity for the plant. In an urban environment this decision is influenced by a variety of factors, of which the most important are: (1) the market for concrete in the area and what proportion is likely to be supplied by ready mix concrete; (2) the share of the market value that an individual depot can expect to obtain; and (3) the expected capital and running cost of a plant (Woodward & Woodward, 1975). However, on the SKA site all concrete will be supplied by an onsite batch plant. Therefore, from an economic point of view, the only factor listed above that is relevant to SKA is (3).

The size of a plant depends on the market share it aims to deliver to. Thus the size of a batch plant on the SKA site must be sufficient in size to deliver the monthly required concrete volumes. According to the interview with Hennis van Zyl (19 Februarie 2015), the area manager of Lafarge (Cape Town office), this is the information an RMC supplier requires to plan for the concrete supply on site. The number of trucks used will vary, depending on the concrete volumes that need to be delivered.

Once plant is in operation it is the task of the RMC dispatcher to deliver all received orders within the day (Maghrebi, Travis Waller & Sammut, 2014). This is a significant task, since they must try to supply concrete to customers at the lowest possible cost. He does so by finding appropriate matches between available resources and demand locations. For example, when supplying a common 5 m^3 concrete order a dispatcher must decide to supply it from a specific depot, with a specific truck, at a specific time. He must take into account several parameters to ensure the lowest cost while meeting all the customer constraints. Models have been developed to aid mangers in their tasks, such as the one developed by Shangyao et al (2006) that integrates the RMC production scheduling and truck dispatching. Also, models have been developed to assess the accuracy of an expert's decisions and also to aid him in the process

of making decisions (Maghrebi, Waller & Sammut, 2013). Such models may represent for example a data set which comprises 4 depots and approximately 40 trucks that have to supply typically 40-200 deliveries per day.

RMC problems have been classified as a specific Vehicle Routing Problem (VRP), or in general a kind of Traveling Salesman Problem (TSP). Most of the research in this domain have focused on implementing heuristic techniques, of which genetic algorithms (GA) have been highlighted more than other metaheuristic methods (Maghrebi, Waller & Sammut, 2013). The practicality of models depends on the number of constraints that is relaxed and if certain variables such as load/unload time are modelled as fixed parameters.

The same type of problem encountered in the RMC domain has been identified for optimization on the SKA site. This identification is based on the lessons learned from the precursor project MeerKAT, where it was found that delivery of concrete to foundations was slow and a major problem on site. Therefore this domain is explored in this study to implement similar logic in a model which can be used to meet similar objectives on the SKA site.

3.3.3 Ambulance location and relocation models

Emergency systems were investigated, specifically ambulance location and relocation models, since this domain has similar objectives to this study. The emergency service managers must make decisions concerned with the dispatching of vehicles when incidents are reported. One of the main tasks of the manager is to determine the severity and urgency of the incident and to accordingly make a decision on the type and number of ambulances to dispatch. Since time is vital in emergency situations it is very important that vehicles are positioned at location to ensure adequate coverage and quick response time. Certain standards need to be achieved and they include that in urban areas 95% of requests should be served within 10 min and in rural areas they should be served in 30 minutes (Brotcorne et al., 2003). This gave reason to the development of ambulance location and relocation models and the utilization of optimization algorithms.

Most of the models developed in the earlier days were static and deterministic of nature. These were typically meant to be used during the planning stage. They however ignored the stochastic consideration, which then gave rise to the development of several probabilistic models. This was done to reflect the fact that ambulances operate as servers in a queuing system and are sometimes unavailable to answer a call. Dynamic models are some of the more recent models developed to repeatedly relocate ambulances in order to provide better coverage. This overcomes the problem of static models that when an ambulance is being dispatched, some demand points are no longer covered.

Nevertheless, two types of early static ambulance location models developed in industry can be considered important to investigate for the purpose of this study. They include: (1) the location set covering model (LSCM); and (2) the maximum covering location problem (MCLP). These models are formulated with integer and linear programming. The aim of LSCM is to minimize the number of ambulances needed to cover all demand points. If the same theory is applied it can be used in this study to minimize the number of batch plants or storage areas needed to cover the supply of concrete or material to all foundations The MCLP was developed to overcome some shortcomings by rather maximizing the covering range of the population of ambulances. It is clear that both models, LCSM and MCLP, can be useful in their own way. For example, LCSM can be used in situations where it is necessary to determine the right number of vehicles to cover all demands, while MCLP seeks to make the best possible use of available limited resources (Brotcorne et al.,2003).

The application of similar logic to SKA will be beneficial during the identification of the locations of storage yards to ensure that all antenna foundations are reached within a specific time. The same can be said for all other temporary and permanent construction facilities. This will increase the efficiency of the construction operations.

3.3.4 The transportation problem

Under this term a set of problems are grouped that can be addressed by standard linear programming methods, but which can also be solved with a less mathematical-involved technique. This technique was mostly developed and used by distribution industries. The problem describes the situation where a dealer stocks commodities in a number of depots around the country and has to distribute them to customers in various locations. In these situations an important constraint is that there is only a specific quantity available at each depot and an exact number must be delivered to each customer. The objective function of these problem studies is to minimize the total transportation cost of deliveries. In the construction industry the delivery of concrete aggregates, cement and bricks from various sources to different sites are typical examples of problems which can be tackled by the transportation method (Woodward & Woodward, 1975).

The objective is to get the minimum cost plan to transport a commodity from a number of sources (m) to a number of destinations (n). For example, consider 4 reservoirs with different daily quantities available, which must supply water to three towns, each having a different daily demand. It is therefore required to find the optimum allocation for each route (Harris & Mc Caffer, 1980).

From literature five LP methods have been identified with which the transportation problem can be solved. They include (Calis & Yuksel, 2010):

1. Northwest corner method;
2. Minimum cost method;
3. Vogel's approximation method;
4. Row minimum method;
5. Column minimum method.

In Calis & Yuksel (2010) a brief description of each of the method formulations and executions is available. The methods use different starting solutions and they vary in the way they allocate amounts of the commodity being transported. The following are findings from Calis & Yuksel (2010) based on a comparative study of the 5 methods.

- The northwest corner method requires less computation and therefore delivers a quick solution, however that is not adequate compared to the optimal solution.
- The row minimum and column minimum are similar to each other. One is based on the supply and the other on demand. Both are useful in a small number of supply or demand problems. Both their transportation costs are less than the northwest corner method.
- Vogel's approximation method and minimum cost method provide the best initial starting solution since it is very near to the optimal solution.
- Vogel's approximation is used to obtain the shortest route, but therefore is computationally intensive and slow.
- Vogel's approximation and minimum cost method delivers the lowest transportation cost when compared to the other methods.

SKA a practical consideration

In order to show how the transportation problem can be implemented for the SKA project, consider the example of the earth moving operation for the construction of a road, where fill material can be delivered from 3 borrow pits, each with a different capacity, to 4 locations with different demands along a road. It is therefore required to determine the best arrangement of supply and delivery of material in order to minimize transportation cost. The applicability of this example on the SKA site is apparent when the large distances between supply and demand locations are considered. There are many possible configurations of borrow pits, quarries and demand locations available because material will be sourced on site.

Another practical example where such an application can be useful is during the planning of the delivery and installation of the optic fibre cable. During the power deployment of MeerKAT

roughly 200 km of optic fibre cable was installed. Due to this large amount of cable, it does not seem feasible to deliver the entire length of cable to one distribution location. However, it can be much more effective if multiple distribution destinations could be identified and the optimum distribution strategy planned from these locations. It is clear that such an application can be an advantage during planning.

3.3.5 Summary

This section presented an overview of models developed to achieve specific objectives concerning the challenges encountered in (1) the site layout planning domain ; (2) RMC supply domain; (3) ambulance location and relocation models domain; (4) construction material supply domain; and (5) the transportation problem domain. These domain areas were reviewed in order to develop a model that can overcome similar challenges identified in SKA. The main focus of this section is construction site layout planning. It entails a review on various research developments and include static and dynamic models, interactive vs. black-box systems and site layout integrated with material procurement planning.

3.4 Optimization Methods

In this section various optimization strategies were investigated. These are to solve problems in the construction and engineering industry, and particularly in site layout, material procurement and supply and repetitive project scheduling models. The section addresses strategies used by researchers in the development of optimization models similar to the ones developed in this study.

3.4.1 Optimization Problems

Many optimization problems of practical as well as theoretical importance contribute to the search for a "best" configuration from a set of variables to achieve some goals (Blum & Roli, 2003). For example, on the SKA site the goal would be to determine the optimal configuration and location of facilities in order to minimize transport cost and time on site, or to select the most feasible work crew formations in order to maintain a constant production rate, while achieving resource continuity.

The optimization problem can be either considered as continuous or combinatorial (Blum & Roli, 2003). If the site layout problem is considered and locations of facilities/departments/offices are predetermined, the problem is typically a combinatorial optimization problem. If locations of facilities are not predetermined, the problem becomes continuous because coordinates of locations then need to be determined (Liao et al., 2010). The project scheduling problem that involves the determination of activity starting times or

resource allocation is typical of a continuous optimization problem (Liao, Egbelu, Sarker & Leu, 2011).

Many construction site layout models are formulated as a combinatorial problem that involves the arrangement of a set of predetermined facilities on a set of predetermined sites, while satisfying a set of layout constraints and optimizing layout objectives (Yeh, 1995). The principle objective is to determine which of the combination of the pre-determined set of construction facilities is optimal in terms of minimizing the total cost and time.

If an example, involving (n) facilities are considered, the number of possible alternatives, that is the number of feasible configurations, is $n!$ This can become a huge number. For example, if 10 facilities are used, the number of possible alternatives is over 3,628,000 and for 15 facilities already in the 12-digit numbers. In practical application a project with $n = 15$ is still small. The suitability of a configuration is measured based on how well it satisfies the objective function which is normally a cost function (Blum & Roli, 2003). El-Rayes et al. (2009) used a grid to represent the possible locations for the centre of each facility on a construction site.

Construction projects are very complex because of the fact that they differ from one project to another. One of the main complexities that construction projects face is the presence of multiple and conflicting objectives (Woodward & Woodward, 1975). In the section that follows multiple objective decision making is discussed.

3.4.2 Multiobjective decision making

Objectives are said to be conflicting if trading an alternative with a higher achievement measure comes at a higher cost. For example, reducing travel time on site may increase congestion, therefore good site layouts must meet multiple, though often conflicting, objectives (Tommelein, 1992). Construction managers must therefore make analytical decisions to achieve these objectives in order for the project to be successfully completed in terms of all the objectives. However, in construction these analytical decisions do not remain the same, since the importance of each of the objectives differs from one project to the next. For example, in one project time might have a high importance, therefore some trade–off on cost will be required; however, on a different project lower cost might be more desirable.

Optimization problems with multiple objectives increase the complexity of the problem and have a large multidimensional solution space as a result. In order to find optimal solutions to such problems in a realistic time frame, sophisticated search techniques need to be utilized.

There are various methods available to solve multiobjective optimization problems. However they will be discussed later in §3.4.5, since it is first necessary to review the different

optimization techniques available and how they are executed to find optimal solutions. Applications of models that utilize these algorithms to solve problems that are similar to this study are reviewed simultaneously. This is done to shed light on the practical application of such methods in industry, especially the construction industry.

3.4.3   Optimization techniques

Optimization models are classified by the type of optimization technique or algorithms it utilizes to search for the optimal solution. Models can either be static or dynamic, depending on whether they re-evaluate the problem over the project duration. Search algorithms search the solution space for either an exact or an optimal solution to the optimization problem. There does, however, not seem to be full consensus on a standard classification for optimization search methods in the literature (Colmant, 2015).

According to Kandil, El-Rayes & El-Anwar (2009a) the type of algorithms optimization models use, can be categorised into two main types: (1) naturally inspired algorithms that mimic a natural process in their optimization approach and (2) analytical algorithms that use a mathematical approach to the optimization problem. According to Blume et al., (2003) this categorisation is not complete and not very meaningful since it is sometimes difficult to group them into one of the two classes. Under these two categories many variations of methods are available that can be grouped under different optimization techniques. Therefore it is first necessary to review the different optimization techniques and then the types of algorithms used by these techniques.

According to Coello et al., (2002) a general way of differentiating between different types of optimization techniques is to classify them as enumerative, deterministic or stochastic (random). In Colmant, (2015) such techniques are further classified as exact, heuristic or metaheuristic. In Figure 3.4 examples of the search algorithms are presented, categorised according to optimization techniques.

Enumeration techniques evaluate every possible solution in the solution space of the optimization problem, either explicitly or implicitly. These techniques are possibly the simplest of search strategies and are guaranteed to find an optimum solution in cases where the problem is simple and the search space is small. However, when dealing with large optimization problems, enumeration approaches may be insufficient (Colmant, 2015).

Deterministic algorithms use problem domain knowledge to reduce the size of the problem's search space. The aim of implementing problem domain knowledge is to guide or restrict the search to finding a good solution in a feasible time. However, multidimensionality of the search space as a result of so many real-world problems can often cause deterministic methods to

be inefficient due to the method's dependence on problem domain knowledge (Coello, Van Veldhuizen & Lamont, 2002).

Many optimization problems are based on real-world problems that have multiobjectives (i.e. to minimize cost and time) and as result of the multidimensionality of the problem it becomes irregular and increases the search space. Given the complexity of these multidimensional problems stochastic search methods were developed as an alternative for solving such irregular problems. They work on the basis of performing probabilistic (i.e. random) sampling of a set of possible solutions and keeping some form of record of good solutions found (Coello et al., 2002).

	Enumerative	Deterministic	Stochastic
Exact	Full Depth First Search Full Breadth First Search Full Branch-and-Bound	The Simplex Algorithm	Full Simulated Annealing
Heuristic	Rule-Based Partial Enumeration	Greedy Heuristics Gradient Methods	Random Walk Monte Carlo Simulation
Metaheuristic	Intelligent Partial Enumeration	Tabu Search	Truncated Simulated Annealing Particle Swarm Optimisation Ant Colony Optimisation Evolutionary Algorithms

Figure 3.4: Search categories and examples of techniques (Colmant, 2015)

Metaheuristics are typically high-level strategies which guide an underlying more problem specific heuristics (Blum & Roli, 2003). Their main goal is to avoid the disadvantage of iterative improvement by generating starting solutions in a more intelligent way than just providing random initial solutions. Metaheuristic techniques can be categorised by the type of search strategy it utilizes, which can be either trajectory-based or population-based. Trajectory methods start with a single initial candidate solution and, at every iteration, replace the current solution with a different single candidate solution (e.g. simulated annealing, tabu search or variable neighbourhood search). Population-based metaheuristics, on the other hand, start with an initial population of multiple candidate solutions, which are enhanced through an iterative process by replacing part of the population with carefully selected new solutions (e.g. genetic algorithms (GAs), ant colony optimisation (ACO) or particle swarm optimisation

(PSO)). In the field of construction layout optimization, planners often resort to using heuristic methods to reduce their search for optimum solutions. However, although heuristics might help finding good solutions on a sophisticated basis, they may not necessarily find the best solution (Jang, Lee & Choi, 2007).

Metaheuristics have become a very popular technique for solving multiobjective optimization problems. The findings from Liao (2011) suggest that anything that cannot easily be solved by conventional exact optimization techniques (analytical algorithms) and specifically designed heuristics is a candidate problem for metaheuristics. Some of the characteristics of metaheuristics that contribute to their popularity are, according to Suman & Kumar (2006), their ability (1) to find multiple solutions in a single run; (2) to work without derivatives; (3) to find Pareto optimal solutions with great speed and accuracy; and (4) to handle both combinatorial and continuous problems.

Methods also exist which can be grouped under the rubric mathematical programming which deliver exact solutions (analytical algorithms). These methods can be classified as linear-, non-linear-, deterministic- or stochastic programming (Coello, Van Veldhuizen & Lamont, 2002). These methods use constraints as the main aspect to the problem. Linear programming is used to solve problems where the objective function and all constraints are linear. Accordingly, non-linear programming methods have been designed to solve multiobjective problems which do not meet those restrictions and require convex constraint functions. Stochastic programming is used when the problem formulation requires the use of random-valued parameters and objective functions based on statistical perturbations. In conclusion, several variants of these method are available, depending on the type of variables used in the problem (i.e. discrete, integer, mixed integer, binary).

Typically the robustness of optimization algorithms are measured in terms of their ability to perform well in terms of computational speed and solution quality. In the section that follows the analytical and naturally inspired algorithms most widely encountered in optimizing problems in the construction industry, are presented in various amounts of detail.

3.4.4 Optimization algorithms

Analytical algorithms

There are different conventional mathematical approaches available to find solutions to the time-cost function in a trade-off analysis. These methods include linear programming, integer programming, and a hybrid of linear and integer programming (Yang, 2007).

Mathematical algorithms have been implemented in various optimization problems and in the construction domain, typically in the construction site layout problem. This research started in Operational Research in the area of facility layout in industrial engineering (Easa & Hossain, 2008). However, the site layout problem has proven to be very complex as the problems expand. It normally involves integer non-convex optimization and requires extensive amounts of computation. Therefore researchers focus more on a heuristic model that find near-optimal solutions instead of mathematical models that deliver exact solutions. Moreover, when developing analytical models the user needs great skills to model the problem. The factors mentioned have limited the implementation of mathematical optimization for site layout and other optimization problems.

Mathematical algorithms have, however, simplified the real world with applications such as clever geometrical constraints (Easa & Hossain, 2008). For example, site facilities were generally dealt with as points where their dimensions were ignored (Tommelein, Levitt & Hayes-Roth, 1992b), but with mathematical formulated models considering continuous space in locating the facilities, many physical and functional constraints are offered. These constraints include object adjacency constraints, facility proximity constraints, object–region constraints, flexible orientation of objects, visibility constraints, and non-rectangular objects and construction areas (Easa & Hossain, 2008:653).

Naturally inspired algorithms

The paper by Liao et al. (2011) presents a detailed review of previous studies that employed metaheuristic optimization techniques to address problems encountered in the life-time of construction engineering projects. The problems encountered are organised around cost estimation, planning, scheduling, and monitoring and control of project operations with the objective to optimize cost and time of resources. In Kandil et al.(2009), various examples are listed where naturally inspired algorithms have been used to solve multiobjective and engineering management problems: (1) deterministic and stochastic time-cost trade-off analysis for construction planning; (2) site layout planning; (3) linear repetitive project scheduling; (4) post-disaster temporary housing arrangements optimization; (5) repair and rehabilitations planning for bridge management systems; and (6) production scheduling for precast plants.

In the paragraphs that follow the four most frequently encountered metaheuristics techniques will be discussed. The first three methods are population based (GA's, ACO, and PSO) and the last single solution based (SA).

GA's are used as search and optimization algorithms that mimic genetic operations. The basic mechanism of the search proses is that it adopts the survival of the fittest and performs a

structured exchange of genetic materials among population members over successive generations. GA's have been widely used as multiobjective decision-making tools in construction and engineering management problems. These GA's have brought great improvement in the search process for near optimal solutions, especially in problems with a large search space (Elbeltagi, Hegazy & Grierson, 2005).

In Chau, (2004) the approach followed to find a dynamic solution to the site layout problem was split into two stages. The first was a lower level stage solved with linear programming (mixed integer) and the second an upper level stage solved with a GA. The efficiency of this proposed algorithm was compared and demonstrated with case examples. A solution for the lower level linear programming stage was found in instantaneously and the use of the GA in the upper level stage showed a reduced amount of computational effort for finding optimal solutions, compared to using only the mixed integer program.

The ACO is an important, naturally inspired optimization technique that models the natural process by which ant colonies are able to find the shortest route between their nest and their food source (Elbeltagi, Hegazy & Grierson, 2005). This heuristic process simulates the use of pheromone trails, which ants deposit whenever they travel, as a form of indirect communication. The development procedure of an ACO model for the site layout problems is presented in Calis & Yuksel, (2010).

Particle Swarm optimization (PSO) is also a naturally inspired algorithm that imitates how birds find their destination during migration (Elbeltagi et al.,2005). The optimization procedure of PSO involves: (1) local search that mimics the way birds use intelligence to learn from their own experience and (2) global search where birds use social interaction to learn from experience of other birds in the flock (Kandil et al.,2009). An example where PSO is used in a multiobjective optimization model to solve the time-cost trade-off problems can be found in Yang, (2007).

Simulated annealing (SA) was developed as a technique to solve combinatorial optimization problems. SA is a stochastic hill-climbing search algorithm that combines a gradient descent with a random process to find a global minimum of the evaluation function. The combinational iteration may end at a local optimum, depending on the initial layout and generation of alternatives. SA overcomes these local optima through allowing an occasional decrease in the quality of the evaluation function (Tommelein, Levitt & Hayes-Roth, 1992b). Although changes that increase quality of the evaluation function are always accepted, a move that impairs the quality will be taken with a Boltzmann probability. However, the probability of doing such a move is decreased during the search. SA has been effectively used, but in very large problems

it requires unacceptably large computing times. SA uses a sequential computational procedure, and efforts to make it parallel have not been that successful (Yeh, 1995).

According to a comparative study, performed by Elbeltagi et al., (2005) on several evolutionary based optimization algorithms it was found that the PSO method generally performed better than other algorithms when considering success rate and solution quality. However it was second best in terms of processing time.

Concluding remarks

According to a study performed by Liao et al., (2002), it was found that EA's/ GA's are the most popular of the metaheuristic methods applied to the construction and engineering management industry. According to them their popularity can be attributed to at least the following : (1) EA's/GA's are the earliest population-based metaheuristics developed; (2) EAs/GAs are capable of dealing with both continuous functions and combinatorial optimization problems; (3) EA's/GA's generally find good solutions; and (4) there are several non-commercial EA/GA tools available for free download. Moreover it was also found that of the related problems that employed metaheuristic, site/floor layout, time-cost trade-off analysis, and resource allocation were most frequently studied. Although GA's are the most popular they have a long computational time when single computing techniques are used. This can, however, be improved by parallel computing (Kandil, El-Rayes & El-Anwar, 2009b). In terms of site layout optimization GA has many capabilities and can handle facilities with various shapes and sizes while accommodating several physical constraints (Easa & Hossain, 2008).

The study by Kandil, El-Rayes & El-Anwar, (2009b) presented a comparison of the robustness of an analytical and naturally inspired optimization algorithm. The comparison entailed an evaluation of the algorithms in terms of their efficiency in optimizing large scale real-life construction problems in a practical and feasible time and also in terms of finding optimal or near optimal solutions. It was found by implementing both algorithms on two case studies that the optimization effectiveness and efficiency of the analytical algorithms out-performs those of the analysed naturally inspired one. This is due to the quality of the generated optimal trade-offs and computational efficiency. However, some construction optimization problems may not be good candidates for analytical optimization algorithms. In these cases the problems are best solved with naturally inspired algorithms, in combination with parallel computing paradigms, to enhance computational time and efficiency.

3.4.5 Solving multiobjective optimization problems

The solving of MOP can be classified into two general approaches, the first being a simple approach that entails converting the multiple objectives into a single objective function by weighting them (Liao, 2011) or moving all but one objective to the set of constraints. The former case is possible with methods such as utility theory and the weighted sum method. The problem, however, lies in accurately assigning weights or utility functions to characterise the decision makers' preference (Konak, Coit & Smith, 2006). Therefore scaling among objectives is required and the drawback is that even small perturbations in weights can sometimes lead to different answers. In the latter case, the problem is that, in order to move objectives to the constraints set, a constraining value must be assigned to each of the former objectives. In both these cases the result of the optimization is a single solution rather than a set of solutions. Decision makers would rather prefer a set of good solutions that can be examined for trade-offs.

The second approach is to determine the entire set of good solutions, called the Pareto optimal solution set. In this set there exists no alternative outside the set that will be better in terms of specific objectives. The solutions in this set are non-dominant in respect to one another. Accordingly, when moving from one Pareto solution to another, there is always some sacrifice of one objective to achieve a certain amount of gain in the other. Pareto optimal solutions are some-times more desirable than single solutions because they are practical when real-life problems are considered because when making a decision there is always some kind of trade-off. Therefore, solving MOP is to find a set of solutions, of which each one satisfies the objectives at an acceptable level without it being dominated by any other solution (e.g. non-dominant).

3.4.6 Summary

This section presented an overview on various optimization techniques and the associated algorithms utilized in each technique. The algorithms have been successfully implemented by a number of researchers in previous developments to solve a range of multiobjective optimization problems. From the literature review the genetic algorithms (GA's) were utilized the most. However, there are many other optimization techniques available. It was necessary to review this research domain since many previous models such as the ones developed in this study utilized an automated optimization approach. However, with regards to the findings of the previous section, this automated approach should be integrated with human judgement and expertise in order to promote the use of and to acquire the most benefit from these models.

3.5 Construction Planning

It is convenient to separate the network planning methods such as network analysis and the scheduling of repetitive projects from this chapter, where the subject area called *Work study*, will be discussed. Work study is concerned with the evaluation of the methods being used to carry out the operation in order to reduce the cost or time. The focus of this section will be to discuss a modelling technique available to solve problems at the production level of construction. The information included in this section contributed to the development of the Site Layout Planning (SLP) model in this study.

3.5.1 Work study in the construction industry

The objective of a work study is to ensure that the work is done effectively in terms of quantity and therefore it is desireble to eliminate wasted work such as double handling of material. Elimination of wasted work will be achieved through an investigation on how the work is done. For example, the placing of concrete can be studied in terms of the "how" problem. In this example there can be six separate units involved in the operations, namely the batching plant, 4 trucks, and the placing gang. For such problems deterministic construction process models are developed in order to determine the idle times of units and to identify which units constrain the productivity of the system. This section presents an overview on the formulation and implementation of a construction process model with respect to an earthmoving haul operation example.

It is suggested in Woodward, (1975) that when it is required to select an operation that merits detailed study, it is best to focus on basic activities such as excavation, large areas of shuttering, brickwork and placing of concrete, rather than small specialised items. Moreover, the factors that should be taken into account are cost, time, resource availability, quality and safety.

3.5.2 Deterministic construction process models

Deterministic models are developed from operations where the time durations involved are assumed to be fixed or constant values that do not vary over time. These models are for example used to determine the operating units in a dual cycle operation which constrain the productivity of the system. To illustrate this application, a simple earthmoving haul operation is considered where the haul unit, a 30-yd scraper, is loaded using a pusher dozer in the cut area. The cycle involved in the operation can be graphically presented in the model shown in Figure 3.5.
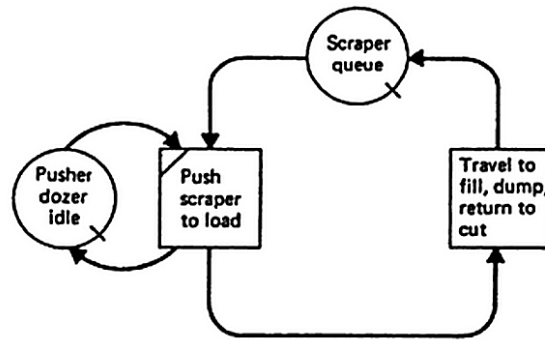
Figure 3.5: Scraper-Pusher dual cycle (Haplin, 1992)

In order to determine the optimum number of scrapers and pushers in the two cycle system, the deterministic work task durations are required. The characteristics can be found in many performance handbooks published by most manufactures. The work task durations are for example the deterministic travel times of the scraper to and from the fill location, as indicated in Figure 3.6.
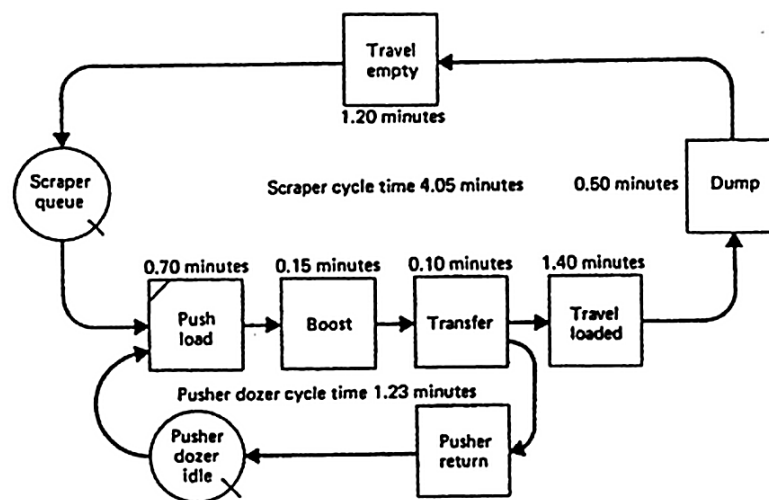
Figure 3.6: Cycle times (Haplin, 1992)

It is clear from Figure 3.6 that there is an imbalance in the cycle time of the two types of flow units in the system. Therefore the pusher is much more productive than a single scraper and as a result it would be idling most of the time, waiting to load the scraper. From this information the system's maximum productivity can be calculated and used in a graphical plot to determine the required number of scrapers that would occupy the pusher most of the time.

A linear plot representing the system's productivity can be developed, such as the one shown in Figure 3.7. This plot represents the increasing productivity of the system as a result of the increasing number of units constraining the system. The balance point of minimum idle time of units can then be deducted from the plot, as shown by the horizontal line on Figure 3.7. The ordinate AB shows that initially almost half the pusher's productivity is lost as a result of the

46

mismatch in cycle times.The imbalance or mismatch of units in a dual cycle system resulting from unit time imbalance between the intersecting cycles is called interference. These models typically do not consider idleness or imbalance because of random variation in the system activity durations (Halpin, 1992).
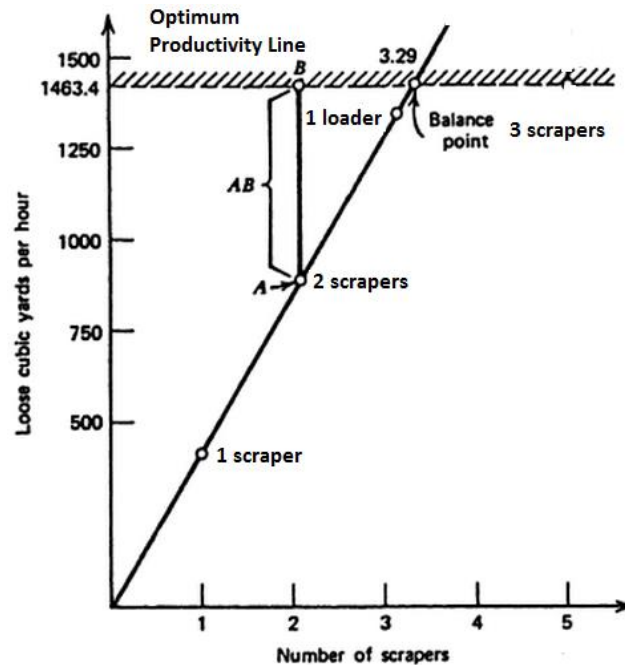
Figure 3.7: Productivity plot

In this study, similar deterministic process models can be developed of the major intersecting cycle, for example the delivery and placing of concrete on site. Similar process models can be formulated for the material supply on site and be included in the SLP model. For example, concrete handling on site can be planned to identify the average number of trucks that is required to enhance the productivity of the delivery of concrete to all antenna foundations. However, in this case, if a few ready mix truck transit unit are added to the system, a waiting line might occur. Therefore Queuing theory is reviewed in the next section.

3.5.3 Summary

This section presented an overview on the formulation of a deterministic construction process model, which can be used for the planning of material delivery on site (i.e. concrete) by integrating it with the SLP model, the objective being to maximize productivity and reduce idle time of resources. Since travel time is an important factor on the SKA site such an implementation will be beneficial. Such an application can be used to plan the delivery of concrete at an antenna foundation.

3.6 Repetitive Project Scheduling

It was mentioned in §1.3 that the construction of SKA antenna foundations fall under the range of projects that require scheduling which will maintain uninterrupted utilization of resources (work teams, equipment etc.). Therefore this section presents a review on the type of network planning methods required to effectively programme a schedule for the construction of the SKA antenna foundations. The reasons why conventional network planning techniques are not sufficient are discussed. The information included in this section contributed to the development of the Repetitive Project Scheduling (RPS) model in this study.

3.6.1 Planning for projects with repetitive activities

Examples of repetitive construction projects include: (1) road projects where the road is subdivided in sections; (2) floors in a multistorey building; (3) houses in housing developments; (4) erecting numerous towers for a new transition line; and (5) meters on pipeline construction.

If for example a road project is considered, the road may be subdivided into sections that will undergo the same sequence of activities during construction. The first and second activities of each section are rough "grading" and "finish grading" respectively. They are followed by several other activities until the section of road is completed. The normal way would be for "work crew 1" who specialises in "rough grading" to start with section one. Once it is completed they will move on to commence "rough grading" in the next section, and so on. After they have generated sufficient working area for follow-up processes, "work crew 2" will follow by starting on section one with the next activity, namely "finish grading". Accordingly this procedure is followed until all the activities in each section are completed.

The construction of antenna foundations also consist of a set number of activities that needs to be completed in sequence. Therefore foundations are considered as repetitive units that must undergo the same set of activities for which each requires specific resources (i.e. work crew, equipment, material) to complete the scope of works.

In this type of projects, construction crews are often required to repeat the same work in various locations of the project, moving from one location to another. The repetition of activities from one unit to the next creates a very important need for a construction schedule that ensures the uninterrupted flow of resources (i.e. work crews) from unit to unit, because it often is this requirement that establishes activity starting times and determines the overall project duration (Harris & Ioannou, 1998), (Mahdi, 2004). Consequently it is an objective to maximize the resource utilization over the project duration.

3.6.2   Scheduling techniques review

Construction management practices use a number of techniques/methodologies that model the sequence and dependencies of project activities. The techniques vary, depending on the project size, complexity, duration, degree of repetition and owner requirements (Mahdi, 2004). Among these techniques, the most accepted in practice are bar charts (i.e. Gantt chart) and network diagrams (i.e. CPM and PERT) (Halpin, 1992). Reasons why previous researchers have classified them as unsuitable for the scheduling of repetitive construction projects are discussed here.

The bar chart

Gantt charts are graphical time scales of the schedule, which is an effective technique for overall scheduling. However they do not show all the inter-dependencies of activities and, specifically for repetitive projects, (refer next section) cannot indicate variation in rate of progress (Mahdi, 2004).

Network-based methods

There are two widely known network-based methods, namely the critical path method (CPM) and the program evaluation and review technique (PERT). Both methods entail showing the work flow schematically by means of arrows that show the logical relationship between the various activities. The main difference between the two methods is that the durations of CMP are more deterministic, since PERT requires three durations in the analysis, which include the most probable, the most optimistic and the most pessimistic. However, these techniques do not model and visualise both the sequencing and execution patterns of activities (Halpin, 1992). This information is important because it creates a better understanding and evaluation of the production process before the operation commences on site (see Figure 3.9).

Typically, CPM only shows technical precedence subject to resource availability constraints, therefore it cannot assure the requirement of uninterrupted usage of resources (Haris & Ioannou, 1998; Mahdi, 2004). The resources-orientated extensions such as resource levelling are also insufficient. Furthermore, the CPM performs poorly in managing and maximizing resource utilization, since it is a purly time-based scheduling approach and not a resource-based approach (Srisuwanrat, 2009).

Line of Balance (LOB)

The Line of Balance (LOB) based models are well suited to control the above mentioned kind of projects (Halpin, 1992). However this method does not supersede the use of networks, but if the two methods are used complementary, they provide a powerful planning tool (Woodward & Woodward, 1975). LOB is a graphical method for production control that integrates bar

charting and production curve concepts (see §3.6.3). The method's focus is on planned versus actual progress for individual activities and graphically displays the difference between the two. It provides managers with information in order to prioritise the reallocation of resources. This is done in order speed up activities that lag behind schedule or to slow activities which are ahead of schedule. By doing this it is obviously assumed that resources are interchangeable, which can cause a limitation on the application in construction.

Concluding remark

With regards to the shortcoming and capabilities of the scheduling methods discussed in this section researchers have developed various scheduling models for construction projects with repetitive activities (Harris & Ioannou, 1998), (Harmelink & Rowings, 1998), (Hassanein & Moselhi, 2005), (Hyari & El-Rayes, 2006). Some of these models will be briefly discussed in §3.6.4. However, although all these model were developed to meet their own specific objectives, they all are alike in that they schedule the work in the project by plotting the progress of repeated activities against time. This can be seen as a form of production curves, discussed in the next section.

3.6.3 The production curve concept

Production curves provide information about the production rate at which sections/units are processed (Figure 3.8), which are required by these types of projects. The rate of production on a construction project normally varies over time and also across work processes, which has a major impact on the release of work for subsequent work processes. For example, considering the construction of an antenna foundation, the rate at which concrete piles are cast is higher than the rate at which foundation footings can be excavated. Therefore these work processes must be properly synchronised in duration and productivity if gross delays and misuse of resources are to be avoided.
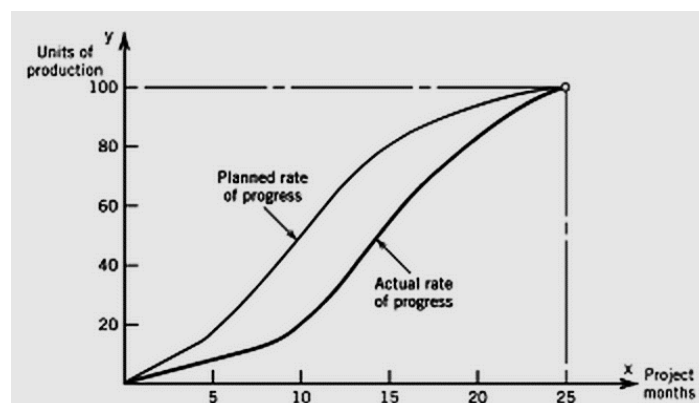
Figure 3.8: Production curve (Halpin, 2010)

The shape of the production curve follows a "lazy s" as shown in Figure 3.8. This situation develops due to the variation in the production rate over project duration. For example, at first

there might be delays in the first units, due to mobilization requirements. Thereafter the rate increases and typically decreases at the end when the project nears close out. Therefore the shape of the curve is flat at the beginning and in the end, but steep in the midsection. The slope of the curve is the production rate. As an example the production rate of each of the activities on a road project is shown in Figure 3.9.

The project must therefore be controlled through the balancing of the production rates between activities. If this is not done the production rates of activities will intersect, and affected activities will have to be shut down until more work units are made available for them to proceed. The stoppage of activities causes a ripple effect and results in large delays and misuse of resources (Halplin, 2010).
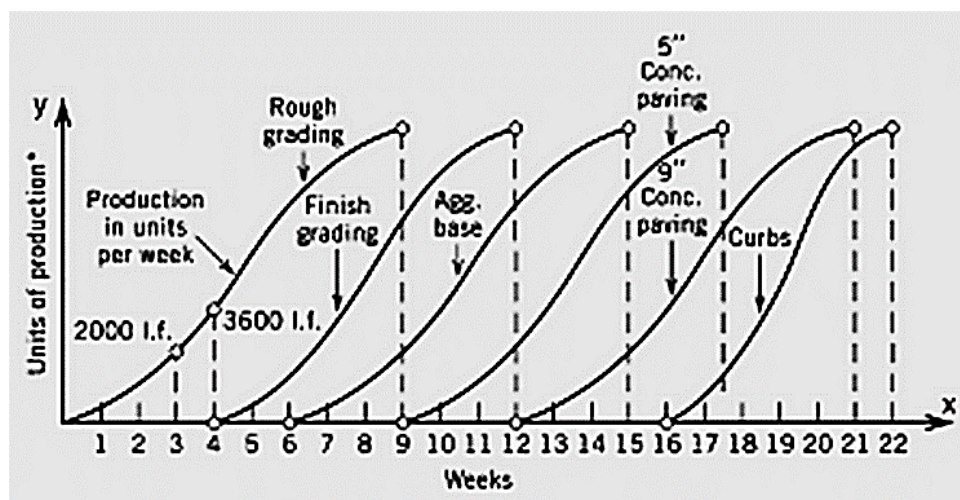
Figure 3.9: Production curve for road construction project (Haplin, 2010)

3.6.4 Previous developments

In this section previous research developments are discussed briefly, in order to provide clarity on some of the objectives of the various repetitive project scheduling models.

The Linear Scheduling Method (LSM) (Harmelink & Rowings, 1998) and Repetitive Scheduling Method (RSM) (Harris & Ioannou, 1998) are two graphical models proposed to identify what was referred to as the "controlling sequence". While LSM accommodates non-repetitive and time-space activities, only repetitive activities can be scheduled using RSM. Although the RSM has this limitation it still has significant advantages over the LSM, due to its ability to reduce project duration based on an identified controlling sequence (Hassanein & Moselhi, 2005).

Reda, (1990) proposed an analytical model that uses linear programming to model repetitive construction projects. The model is mathematically formulated to calculate the quantity of resources for each activity in order to achieve the following:

1. To maintain a constant production rate for the work crews on activities throughout the project.

2. To maintain continuity of work between work crews from one stage to another, thus to eliminate idle waiting for a preceding crew to complete their task.

3. To allow for time buffers between activities at the same stage. For example, to compensate for the time between concreting crew and formwork crew.

4. To allow for stage buffers between activities at different stages. For example, to compensate for the time it takes for concrete to cure before the succeeding activity can start.

5. To complete the project at the minimum cost possible, given a target project duration.

The application of crew work continuity constraints provides for an effective resource utilization strategy that leads to: (1) maximization of the benefits from the learning curve effect for each crew; (2) minimization of idle time of each crew; and (3) minimization of the off-on movement of crews on a project once work has begun (El-Rayes & Moselhi, 1996).

Although maintaining crew work continuity has been a major objective of many models, it has been suggested by Selinger (1980) that its violation, by allowing work interruptions, may reduce the overall project duration and, accordingly, the project's indirect cost. El-Rayes & Moselhi, (2001) implemented two models: (1) a model that provides strict compliance with crew work continuity (Selinger, 1980); (2) a model that allows interruptions to crew work continuity (El-Rayes & Moselhi, 2001). The result is shown by the two schedules in Figure 3.10, indicating the two possible trade-offs between the two important and conflicting objectives of minimizing the project duration and maximizing crew work continuity. However, in Moselhi & Hassanein, (2003) it is said that this might be true for residential buildings but the same argument does not stand for projects with high mobilization/demobilization costs, which is generally the case for linear projects (Moselhi & Hassanein, 2003). The equipment used in these projects is expensive and their idle time is costly and therefore work interruptions should not be permitted in these projects.
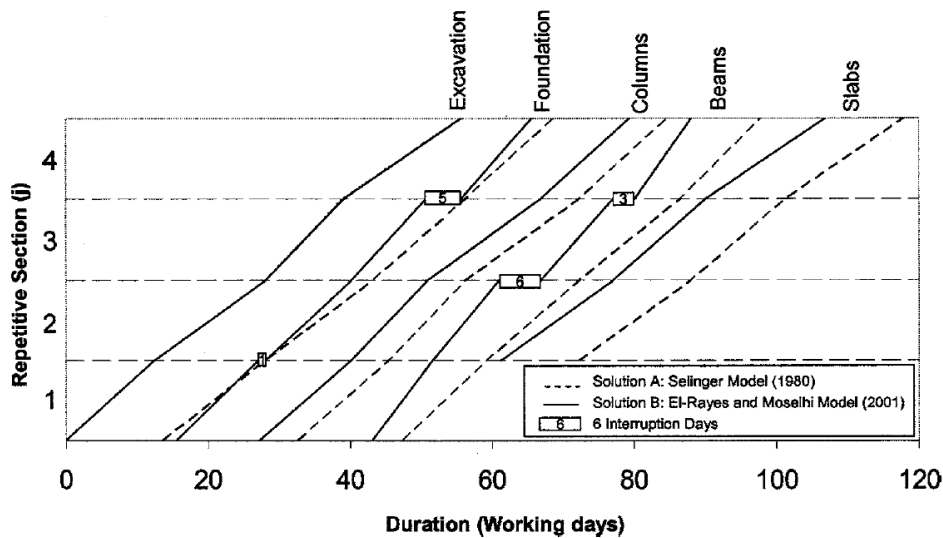
Figure 3.10: Minimum duration solution provided by allowing for crew work interruptions (El-Rayes & Moselhi, 2001)

In another study performed by Hyari & El-Rayes, (2006) a model was developed that can perform multiobjective trade-offs between the two important conflicting objectives of minimizing the project duration and maximizing crew work continuity. These types of solutions make it possible for the manager to evaluate all the feasible trade-offs.

According to Sajay Bhoyar et al., (2014), most existing resource-driven scheduling techniques consider the same resource crew to perform a task in all repetitive units. Therefore a model must be able to generate project schedules considering the simultaneous assignment of multiple crews for each task. In El-Rayes & Moselhi, (1996) a resource-driven model is developed that makes the simultaneous assignment of multiple crews possible.

3.6.5 Summary

This section provided a review on network scheduling methods and previous developments in the field of repetitive project scheduling in order to find suitable techniques to include in a similar repetitive project scheduling model for SKA.

3.7 Chapter Summary

In order to provide SKA INFRA SA with an optimized deployment strategy for the construction of antenna foundations, various literature domains were consulted. From these literature domains, three alternative approaches were selected, since it is assumed that its application would lead to the greatest improvement of the construction operation efficiency in SKA. The approaches are all of quantitative nature and have effectively been applied by previous researchers in order to achieve a variety of objectives in the construction industry. The approaches include: (1) site layout planning which entails designing a near-optimal layout that reduces travel time of labour, material and equipment, and improving the construction productivity; (2) conducting a work study on construction operations, which entails developing a deterministic construction process model for the ultimate purpose of reducing the idling of resources in the construction operations, especially the delivery of material in this study; and (3) scheduling repetitive projects, which entails planning a schedule that strives for a balance between project duration and resource utilization.

Related to the research covered in this chapter, many previous research developments utilize automated optimization techniques, methods and algorithms. Researchers make use of both mathematical and metaheuristic optimization techniques to solve the problems and challenges faced in this research area. However, it has been noted that optimization algorithms cannot easily replace human judgement and expertise, as the algorithms do not always capture the qualitative and intelligence aspect of construction management. Therefore a human interactive component is desirable.

The models that have been reviewed and the motivation therefore, can be summarised as follows

1.	*Site layout planning*	*To plan the site layout in order to effectively deploy resources.*
2.	*Ready-mix concrete*	*To plan material-handling over a large delivery area.*
3.	*Ambulance location*	*To determine the right number of construction facilities to cover all demand locations.*
4.	*Deterministic process*	*To maximize the productivity of operations and reduce the idle time of resources.*
5.	*Repetitive project scheduling*	*To reduce the project duration and maximize the resource utilization.*

The information reviewed in this chapter is taken into consideration during the development of (1) the Site Layout Planning (SLP) model and (2) the Repetitive Project Scheduling (RPS) model. The integration of these two models form the construction deployment planning model for SKA. These developments are discussed in the remaining chapters.

CHAPTER 4

SITE LAYOUT PLANNING (SLP) MODEL

The proposed model is a prototype decision support tool for users to construct site layouts and to develop a project schedule for the construction deployment of antenna foundation in SKA. The model is a 2D interactive management system that comprises two main modules: (1) an interactive site layout planning (SLP) model that entails a manual optimization process through a "what if" scenario simulation analysis; and (2) a repetitive project scheduling (RPS) model that entails the generation of an activity based construction schedule that ensures the un-interruption of resources in the repetitive construction nature of the project. In this chapter the first model, the SLP model, will be described. However, the reader must take note that the second model, the RPS model, is included in some of the descriptive illustrations in order to illustrate the integration of the two models.

Included in Appendix D is a graphical visual representation (see Figure 10.2.) summarising the model formulation on how the two models are integrated. Figure 10.2 is a summary of the unique concepts presented in this chapter and in CHAPTER 5.

4.1   Introduction

The main objective of this chapter is to develop a simulation-based, dynamic site layout planning (SLP) model that is capable of minimizing layout costs (i.e. transportation cost on site, site establishment cost etc.) and improving construction productivity by minimizing travel times of labour, material, and equipment on site. The proposed model is designed as a visual communication tool through a graphical user interface (GUI) that allows the user to be in control of the proceedings and to retrieve the results of various layout alternatives (discussed in CHAPTER 6). The development of the model involved three main steps: (1) formulating the SKA site specific layout planning problem; (2) modelling the space-time representation of the construction site and facilities in an object-orientated programming environment; and (3) integrating the model and user with a GUI.

The simulation-based SLP model can serve as the framework for further development, such as an automated optimization module that executes a metaheuristic algorithm on this framework to search for the most feasible trade-off (i.e. cost and time) and support human intuition.

This chapter provides a brief overview on the objective of site layout planning, discusses the rationale behind the formulation and architecture of the model, describes when and how it is

used in the planning life cycle, explains how the quantitative measures are calculated and executed, discusses room for developing an automatic optimization framework and lastly gives feedback regarding two developed model extensions.

4.2   Overview on the objective of site layout planning

When designing a good site layout there are high-level objectives that need to be achieved, such as getting the project built on time and within budget, promoting safety, maintaining good employee morale, and achieving efficient operation. However, these objectives do not prescribe how the site layout must be performed and therefore, alternatively, there are low-level objectives that can prescribe in more detail (Tommelein, Levitt & Hayes-Roth, 1992b). These low-level objectives are more quantifiable. For example, one should minimize travel distance and time for movement of personnel and equipment between parking and work positions, between field offices and work areas, and between supply sources and work areas; low ratio of material handling time to production time; and one should avoid creating obstacles for material flow. However, since these low level objectives are "localized" they may not provide global criteria to judge the overall site layout (Tommelein, 1989). The next section will describe how the model is formulated and how these objectives have been captured in the model.

4.3   Model Formulation

The site layout planning (SLP) model is a manual-based dynamic planning framework where users can interactively make changes to the site's layout across various construction stages in order to meet a specific objective. The model was designed to be interactive in order to get a good hold on the trade-offs between the multiple objectives of site layout planning. Layout changes might entail:

(1) adding more facilities to the construction site in order to reduce the average transfer time of resources traveling from a particular facility;

(2) moving a facility in succeeding construction stages, to be closer to the foundation units being constructed.

In essence the user is free to access specific decision variables through a GUI and to change them to perform various kinds of trade-offs in order to deliver the most effective construction layout in terms of multiple objectives. Therefore the site layout is optimized through an interactive manual simulation process and not through an automated optimization framework that operates like a black-box (see §3.3.1). Rather, the model is a decision-making tool to assist a manager during the construction planning of SKA.

The model is formulated in this way so that construction managers who understand the complicated process of designing a site layout, can understand and use the model to create their own site and constraints. The model then captures the manager's layout decisions and measures the effectiveness of his/her decisions on a quantitative basis, rather than solely relying on practical experience and gut feeling if the model is not available. The model is then integrated with a RPS model which automatically generates a construction schedule (discussed in CHAPTER 5).

4.4   System Architecture

The proposed models (SLP and RPS) were developed in Java, using Eclipse software. Eclipse is an integrated development environment (IDE) and is primarily used for developing Java applications. Java is an object-orientated programming language, which has been in use for more than 15 years. Since it is well supported and used by many software developers and vendors it can be considered as a mature programming language. Also, applications can be easily developed due to open source code and available examples. It is for these reasons that the model is developed in the Java programming language.

In order to visualize the design of the system the Unified Modelling Language (UML) is used. The UML class diagram of the complete model is shown in Appendix H, Figure - H.1. This diagram is a representation of the source code and graphically illustrates the relationships between classes in the object-orientated environment. This standard form of illustration allows key concepts of the framework to be understandable to a large audience.

Furthermore, the source code was created in such a way that it is easily understandable for the reader upon examination. For further clarification of the model, the reader is advised to examine the accompanying source code.

The diagram shown in Figure 4.1 shows how the different parts interact with each other. The user interacts with the GUI, which then modifies the model based on the input from the user. The view provides a graphical illustration of the information stored in the model.
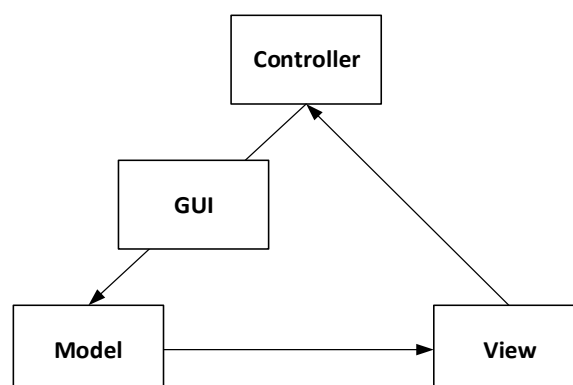
Figure 4.1: Model-View-User Architecture

The list that follows below is a description of the main class objects that form the building blocks of the SLP model. The important concept below will be discussed in more detail in §4.4.1, §4.4.2 and §4.4.3.

- *Location:* Objects of this class represent points in a 2-dimensional plane and has a *Point2D* attribute.
- *Point2D:* Objects of this class have x- and y-coordinates and provide methods to get- and -set these values.
- *Sources:* Objects of this class represent temporary construction facilities on site and are a subclass of Location.
- *Facility:* Objects of this class represent the family of the same type of sources.
- *FacilityTraits:* Objects of this class comprise the set of attributes that belong to a specific type of facility (*Facility*). It is this object which makes a batch plant different from a storage yard. When a source is added to the construction site, it inherits the *FacilityTraits* of the *Facility* to which it belongs.
- *Destination:* Objects of this class represent a demand destination on site and are subclasses of *Location*. Each *Destination* object has a set of demands of which each one must be supplied by a source on site (i.e. Foundation has a concrete demand that must be supplied by a batch plant and a steel demand that must be supplied by a steel yard).
- *Foundation:* Objects of this class represent antenna foundations on site and are subclasses of *Destination.*
- *DemandObject:* Objects of this class describe the attributes of a demand. Each foundation has a set of *DemandObject*-objects, which are supplied by the various sources on site.
- *Site:* Objects of this class represent the site and contains all the destinations and sources on site.
- *NamedObject:* Objects of this class have a name and a value. This object makes it possible to easily add attributes to *Sources* and *DemandObject*-objects without changes in the core of the program.

In the sections that follow the important concepts of the SLP model's architecture will be introduced. These concepts include: (1) Concept behind a Facility; (2) Concept behind a DemandObject; (3) Concept behind a Connection. After this discussion the reader will have a better understanding of the model's structure. In brief, the discussion of each includes the following:

1. Concept behind a Facility – How a generic construction facility is designed and added to the model;

2. Concept behind a DemandObject – How a specific demand is assigned to an antenna foundation;

3. Concept behind a Connection – How facilities are connected to a foundation and Constraints are added to facilities.

The model formulation is graphically presented in Appendix D, Figure 10.2.

4.4.1 Concept behind a Facility

Temporary construction facilities are required to support the construction works on site. They are site-level facilities such as batch plants, storage yards, and fabrication yards etc. Each construction facility may also be accompanied by an intermediate transfer centre (Chau, 2004).

Tommelein, (1989) compiled a detailed list of temporary facilities commonly encountered on construction sites. This can be used by field managers as a checklist to identify the types of facilities needed. It is proposed by Tommelein, (1989) that material handling equipment (i.e. trucks) be added to this list, which was done in this study by designing a *Facility*-object that has this attribute. It is said that the location of such equipment can have a major impact on the location of temporary facilities on site. Therefore the location of these dynamic entities is defined by the facility to which they belong and how they move about on site is determined by the simulation-based model of the material delivery to demand destinations.

The Facility-object (i.e. *Batchplant*) was created in order to intelligently distinguish between various construction facilities on site. In the SLP model, construction facilities are represented by *Sources.* On site it might be desirable to have more than one source of the same type (i.e. *Batchpant1* and *Batchplant2*). In this case Sources of the same type are stored in a *Facility* object. Basically a *Facility* signifies a family of sources. When a *Source* is added to the model it is automatically saved to the right *Facility* (family) and it inherits the *FacilityTraits* of that family. The Facility-object is designed to be of a generic type, in order for managers to create their own facilities to support the construction operations on site. It is this concept that makes it unnecessary to change within the core of the program, when a new *Facility* object is required for customisation reasons e.g. a Pre-fabrication yard. This means that a custom type facility can be created and stored in the Model of the application without any changes to the Model. It is also this concept that makes it possible to distinguish between the types of facilities on site and how many of each there are.

Facilities are created according to user specifications, i.e. Table 4.1 represents the standard *FacilityTraits* that are specified by a user during the creation of a *Facility*. In the case where it is required to add a facility trait which has not been compensated for, it can be included in the

model with ease without changing the core of the program. Once the *FacilityTraits* of a *Facility* have been specified and added to the model, a facility (*Source* object) is ready to be added to the construction site. Therefore the only information which is required when adding a *Source*, is its co-coordinates on site (shown in Table 4.2) and the *FacilityTraits* it will inherit as soon as it is added to the site. Table 4.1 has a list of the type of attributes of a facility.

Table 4.1: FacilityTraits information

Name	Batch plant
Install cost	R750 000
Number of trucks	4 RMC trucks
Truck volume	6 m^3
Operating time	5 hours/day
Unloading time	10 minutes
Max delivery time	2 hours

Table 4.2: Source information

Name	Batch plant 1
x-coordinate	5
y-coordinate	3

Discussion of the attributes of a FacilityTraits object:

1. *Name:* Refers to the name of the *Facility*.
2. *Install cost:* Is the capital cost of establishing the construction facility on site.
3. *Number of trucks:* Is the number of trucks operating from a temporary construction facility.
4. *Truck volume:* Is the volume of the commodity at the facility which a truck can transport.
5. *Operating time*: Is the allowable daily operating time of a temporary construction facility.
6. *Unloading time:* Is the deterministic time it takes for a truck to unload, operating from that particular facility.
7. *Max delivery time:* Is the maximum allowable time a delivery may take i.e. cold joint time of concrete. Construction managers may also specify that the transportation of resources to and from a site camp should not take longer than 1 hour in the morning. The model will then calculate which foundations are at a distance from the site camp that violates this constraint.

4.4.2   Concept behind a DemandObject

Each antenna foundation has a set of *DemandObject.*-objects (i.e. concrete, steel, shutters etc.). This demand is represented by a *DemandObject*. A *DemandObject* represents the connection between a *Foundation* and a *Facility*. If a *Foundation* has a *DemandObject* which must be supplied by a *Facility*, a connection exist between the *Facility* and the *Foundations.* The user can create any material *DemandObject* and Facility to supply demand. For example water for concrete manufacture can be assigned as a *DemandObject to a foundation unit* in

the model. The respective sources for water supply must then be accordingly inserted in the model.

Table 4.3 lists the attributes of a *DemandObject*. The shaded part of Table 4.3 is determined once the simulation executes and the remainder must be specified by the user during the creation of a DemandObject. Below the table is an explanatory list of attributes used in the Table 4.3.

Discussion of the attributes of a DemandObject:

1. *Demand:* The *Demand* attribute shown in Figure 4.2 is of type NamedObject. This implies that a demand-object has a *name* and a *value* attribute, discussed below.

Table 4.3: DemandObject information

Name	Batch plant
Value	72 m3
Type of Demand	Supply
Material	Concrete
Supplier	Batchplant1
Time	15min
Has a Source	True
Served time	1 hour 15min
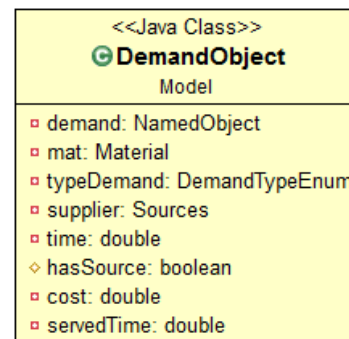
Figure 4.2: *DemandObject* UML

2. *Name:* Indicates which *Facility* type must supply the demand *value*. However, if for example there are more than one Batch plant, there are two sources for concrete. Accordingly, the model must then calculate which one of the *sources* are the closest (refer to point 5, below).

3. *Value:* Refers to the quantity of the demand that must be supplied at that specific destination on site.

4. *Type of demand:* Indicates whether the demand is a quantity that requires a material "supply" or a demand which requires a "visit" from a resource.

5. *Material:* The *Material* object represents the commodity that is being transported from the *Facility* to *Foundation* (i.e. concrete, steel etc.) and has a direct cost associated with it.

6. *Supplier*: During the simulation, it is determined for each of the *DemandObject*-objects assigned to a *Foundation*, which of the sources available on site can supply its demand the quickest and then assigns that source as its supplier. For example, in the case where there are more than one source on site for concrete, i.e. two batch plants, the algorithm calculates which of the two sources are the closest, checks that it satisfies the time constraint and assigns its as its supplier.

7. *Time:* Refers to the time it takes to travel from the source to foundation.

8. *Has a Source:* A *DemandObject* has a supplier if the supply time is less than the maximum allowable time constraint. Otherwise, if this constraint is exceeded, there is no supplier for that *DemandObject* of that specific foundation. In this case that foundation is added to the set of undeliverable destinations of the source with the shortest supply time.

9. *Served time*: The time it takes to supply the full quantity of the demand. This parameter is also dependent on the number of trucks that operate from a facility and their capacity, i.e. more delivery trucks will result in a faster delivery; similarly, if the capacity of the trucks are increased, the number of trips are reduced therefore shortening the supply time.

Example:

It may be known that a foreman will travel three times each day from a site camp to a foundation. The DemandObject will then be created with name: "site camp", it will be of type: "visit" and value equal to 3. Moreover, in the case where each foundation requires 72 m^3 of concrete, a DemandObject will be created with name: Batch plant, type: "supply" and the value equal to 72. The simulation uses this information to accurately calculate travel frequencies and transfer times.

4.4.3 Concept behind a Connection

It is here where the connection and dynamic flow of entities (i.e. trucks and resources) between demand destinations and construction facilities are discussed. In the model, travel between *Locations* is specified by connecting them.

These connections can be classified as two types. The first is the most obvious and is defined as Facility-Foundation connections. They represent the transportation between various construction facilities on site and the foundations for either the supply of material or travel of resources. The other type of connection can be defined as Facility-Facility connections, which are better understood as constraints. They are more complex and are added as constraints to each of the facilities to which they apply. Both are discussed in more detail below in terms of how they are created and added. Both these concepts are essential during the execution of the model and this is one of the model's advantages since users don't have to compile large, complicated and unintuitive matrices that symbolise the rate of travel between facilities, such as in many other models of this kind (Yeh, 1995), (Cheng & O'Connor, 1996), (Easa & Hossain, 2008). These two concepts are graphically illustrated in Figure 4.3.

Facility-Foundation connection

A connection between a *Source* and a *Foundation* exists, if the foundation unit contains the *DemandObject* that must be supplied by that specific source (i.e. facility type). Therefore, in

order to create a connection between a batch plant and a foundation, a batch plant-*DemandObject* is created and added to a Foundation (Red dotted line in Figure 4.3). If a Foundation does not include the *DemandObject* of a specific type of Facility, then that Facility will not be connected to a Foundation.

Facility-Facility connection

Facility-Facility connection can be seen as constraints and refers to the transportation between construction facilities. Two types of constraints have been designed and can be classified either as *transfer-* (green on Figure 4.3) or as *visit* (purple in Figure 4.3) constraints. For example, it might be required during the supply of material (i.e. steel) from a storage yard, that a delivery truck should stop at the site camp to pick up equipment before delivering the material at the foundation site. In this case the site camp is a "transfer" constraint for the storage yard (green in Figure 4.3). In a different case, it might be known that five times each day there will be a trip from the site gate to a batch plant. In this case the site gate will be added as a "visit" constraint for the batch plant. The user can define all these practical constraints for construction facilities on site in order to generate more accurate and realistic simulation results.
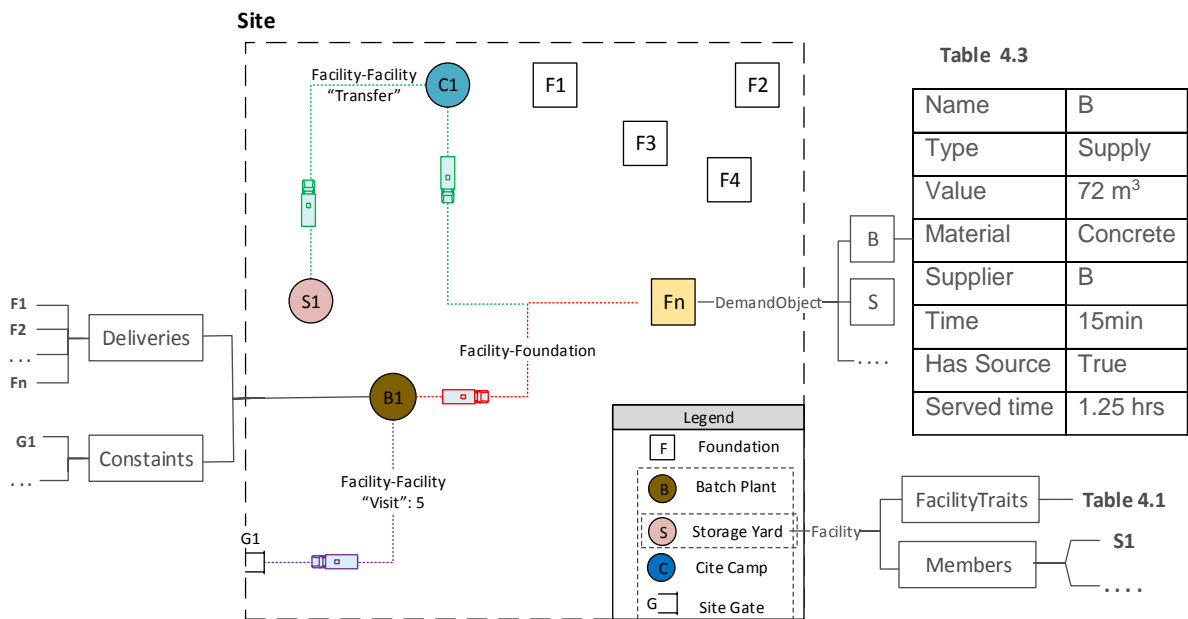
Figure 4.3: Model description of the flow of dynamic entities on site

4.5   Model Description

4.5.1   Interactive optimization procedure

In Figure 4.4 the different phases of the construction deployment planning are shown. It can be seen where the present model lies within the planning life cycle and how it can be used as

a decision-making tool to help optimize the deployment strategy. Figure 4.4 is discussed in more detail below.

Construction Planner Phase: The construction planner must study the project information, for example the SKA dish locations, antenna foundation design and site spatial data.

Preliminary Design Phase: The project specifications and requirements must be defined (i.e. plant-, transportation-, material- and resource requirements) and included in a preliminary construction deployment strategy.
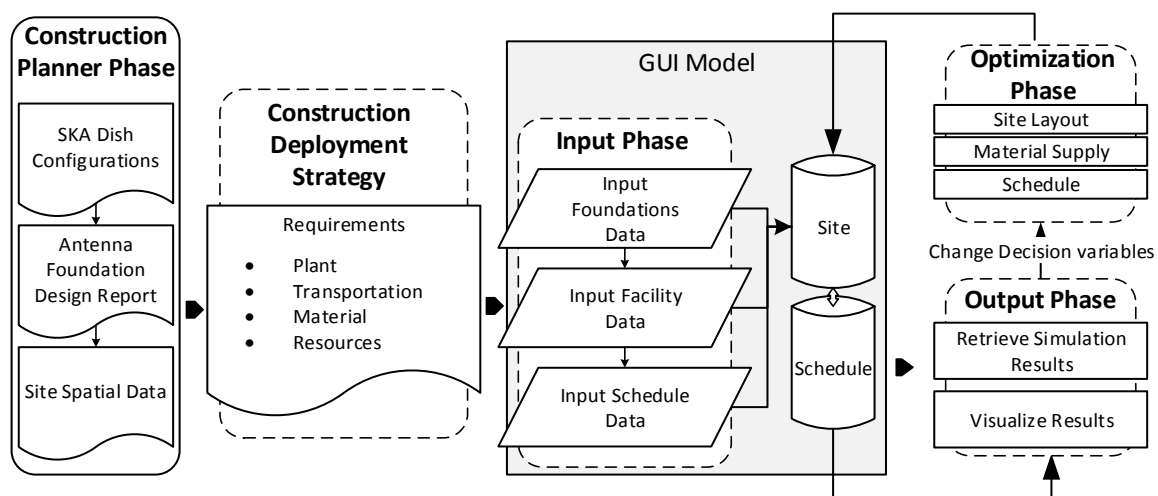
Figure 4.4: Construction Deployment Planning model

Input Phase: The preliminary construction deployment strategy is then imported in the SLP model through the GUI by the user. The user is required to: (1) input all types of temporary construction facilities required on site to support the construction operation, as well as their initial locations; (2) input the location of all demand destinations on site (i.e. the centroid of antenna foundations); and (3) design the flow of dynamic entities on site by connecting them (i.e. see §4.4.3). The scheduling information will be discussed in §5.3.

Output Phase: Once the previous phase has been completed the simulation can be executed to retrieve the results of the effectiveness of the site layout. The simulation provides both visual and quantitative information which the user can use to assess the suitability of the alternative.

Optimization Phase: Various trade-offs can then be performed dynamically by the user by changing decision variables (see §4.7.2) in order to optimize the preliminary construction deployment strategy. The construction schedule is also optimized here by the RPS model (Chapter 5). When a suitable deployment strategy has been designed with respect to the site

layout, the supply of material and the construction schedule, the data can be exported from the model to MS Excel to be further processed for presentation.

4.5.2 Layout constraints

The SLP model includes some theoretical constraints. However, some of the practical considerations, such as some geometric constraints which are more applicable to ordinary construction sites with limited space, were excluded from the model due to obvious reasons. These constraints become more important once an optimization framework is developed, which operates through the SLP model simulation framework. Therefore these constraints cannot be ignored and are worth mentioning and are discussed below:

1. Boundary constraints will ensure that all facilities are added within the site boundaries.
2. Overlap Constraints prevent the physical overlap of any pair of construction facilities in the same construction stage. However, since the SKA site covers a large area, if 2 facilities are located on top of each other, there will be sufficient space to move them. Therefore these are practical constraints and can be extended to also include antenna foundations, for example, to prevent facilities from being positioned on top of a foundation.
3. Min/Maximum distance constraints, are imposed on the face[1] distances between facilities to ensure operational safety and security. For example, the minimum distance construction can commence from the RFI building, without disrupting the radio frequencies.
4. Exclusion/Inclusion zone constraints are imposed to limit the presence of facilities outside or inside a specified zone on site. For example, in the general case exclusion zones can be placed around an access gate to prevent facilities from blocking the access area. The same logic can be applied to prevent facilities from being positioned on a mountain.

Many constraints such as the ones listed above have been developed in previous models (Easa et al., 2008; El-Rayes & Khandaker, 2005; El-Rayes El-Rayes & Said, 2009; Jang et al., 2007).

4.6   Construction project cost

It is necessary to define which cost components were considered during the capital cost estimate in each of the two models developed.

4.6.1   Included cost elements

The construction cost has been classified as direct and indirect cost as shown in Figure 4.5. The cost components included in the RPS model are also indicated in Figure 4.5.

---

[1] The boundary of a temporary construction facility

It has already been mentioned that the management cost of planning a site layout is covered by the overhead cost (i.e. preliminary and general cost (P&G's)). The actual construction site expenses, such as the establishment cost of construction facilities (i.e. batch plant, storage yard) are also an overhead/indirect expense (see in Figure 4.5). Indirect cost, also called overhead cost, is any cost not directly identified with a single final cost objective but identified with two or more final cost objectives.

Material cost is classified as a direct project cost. However the procurement of material on site has various cost components associated with it, which is discussed in the next section.

	Direct Cost	Indirect Cost
SLP Model	Site Transportation	Construction facilities Storage facilities Vehicle hire
RPS Model	Labour wages Material	Construction equipment hire
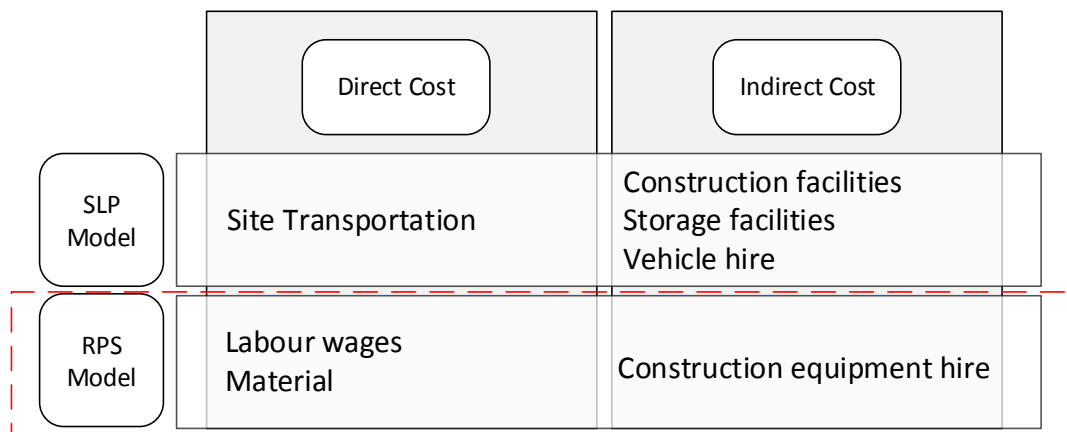
Figure 4.5: Construction Capital Cost Estimate

4.6.2 Material procurement cost

Material procurement planning is an important aspect of construction management and has a significant impact on project productivity and cost. Procuring construction materials involves specifying suppliers, quantities and dates of material deliveries, considering activity demand and site conditions. In the SLP model only the on-site transport cost of material is considered and the purchase cost is considered in the RPS model. However, it is necessary to discuss the other material procurement cost components which managers should take into account when planning a site layout. These material cost components are listed below: (Said, 2010).

Purchase Cost is the direct cost of material acquisition. This cost has both a fixed and a variable component. The fixed component involves the bare cost rate of the material that does not change with order quantity, while the variable cost represents the administrative cost of placing an order that decreases with larger order material quantities. However, it is important to note that the quantity of material ordered in advance determines how much space is required for onsite storage. For simplification the variable portion of the cost is ignored in the SLP model.

Delivery Cost is the expense of transporting material from the supplier to the construction site. Similar to purchase cost, delivery cost rate is reduced when larger quantities of material are ordered. This is because there is greater utilization of truck capacity. Therefore it becomes more feasible, in terms of delivery and purchase cost, to order fewer deliveries with larger quantities, than smaller size deliveries. This cost is not considered and can be added to the model in further research development. The reason why it has not yet been included is that it does not influence the site layout or construction sequence.

Handling cost is the cost of the time it takes for crew to move material from its on-site storage to the construction activity area. It is this cost that is significantly affected by procurement decisions and site layout. Handling cost can be reduced if some of the quantities are delivered from the supplier to the activity location. It can also be minimized if the site layout is designed in a way that locates the on-site material storage area as close as possible to its designated construction areas. The minimization of this cost is the main focus of the SLP model.

Financing Cost is the rate of return one could have expected from the money that is locked up in on-site inventory, if it were to be invested elsewhere. On-site inventory is reduced by smaller, more frequent deliveries. Moreover, expensive resources (i.e. rebar or equipment) generate more financing cost than cheaper resources (i.e. bulk materials such as sand, cement and bricks). Although this is not included in the model, it must be taken into consideration by the construction manager when material procurement decisions are made.

Carrying cost includes any other cost that is incurred by the contractor due to the holding of material on site. This includes storage, management and spoilage.

Stock-out Cost is any cost that is incurred due to the shortage of material when needed, such as project delay penalties and labour waiting times. Cost that is incurred due to labour waiting times is considered in the RPM.

All of the cost components listed above have not been included in the SLP model. However, construction managers must be aware of these cost elements. Including the other cost components within the SLP framework can be material for future research. What has been included is the handling cost, which consists of the fuel cost and vehicle hiring cost. Material will be transported (e.g. handled) with construction vehicles on site, therefore vehicle procurement cost will be discussed next.

4.6.3 Vehicle procurement cost

Vehicle procurement decision variables have been included in the SLP model, and their hiring cost (R/hour) has been added to the transportation cost on site. The focus, however is on the identification of the appropriate number of material handling equipment (i.e. trucks) required that will lead to efficient material delivery. Vehicle procurement decisions were integrated with the SLP model, because it is these decisions that have a direct influence on the delivery time (e.g. handling time) of a demand quantity. These decision variables include: (1) the number of delivery vehicles; and (2) the capacity of delivery vehicles operating from a temporary construction facility.

4.7 Model 1: Site Layout Simulation Algorithm

In this section the algorithm that executes the SLP model simulation will be discussed in terms of (1) decision variables; (2) objective function; and (3) algorithm implementation. The objective of the model was to use an integrated approach that simultaneously simulates two categories of decision variables: (1) site layout decision variables; and (2) material supply decisions variables. However, it is first necessary to state how the transportation distance on the SKA site was estimated, which is discussed in the next section.

4.7.1 Estimating the transportation distance

Transportation distance is one of the parameters that is used in the estimate of the transportation cost of traveling on site. The transportation cost was calculated as shown in Eq. (4.4) and will be discussed in §4.7.3.

The distance between two destinations on the SKA site was estimated by using the Manhattan distance in Eq. (4.1). This is considered as a fair assumption, as opposed to the Euclidean distance in Eq. (4.2), because the roads on the SKA site are not straight from supply to demand locations, but rather they can be represented by the Manhattan distance.

The Euclidean distance is the shortest path represented by the green line on Figure 4.6. The Manhattan distance is represented by the red, yellow and green line, which all have the same length. The latter refers to the grid layout of most streets on the island of Manhattan, which result in the shortest route a car can take between two points, to be the absolute difference of their Cartesian coordinates (distance between two facilities measured along the x and y axis).

$$d_{ij} = \quad |X_i - X_j| + |Y_i - Y_j)| \qquad\qquad \textbf{(4.1)}$$

$$d_{ij} = \quad \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} \qquad\qquad \textbf{(4.2)}$$
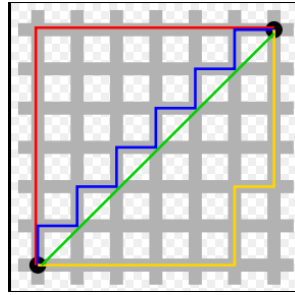
Figure 4.6: Manhattan distance

4.7.2   Dynamic layout decision variables

The layout decision variables are designed to be accessed by the user and changed manually in order to optimize the site layout. Site layout decision variables include:

- The number of temporary facilities on site;
- The location (co-ordinates) of temporary facilities on site;
- The number of trucks operating from temporary facilities;
- The capacity of the trucks.

As mentioned, these decision variables can be changed dynamically over the construction stages. As the construction of a foundation unit is completed it can be removed from the site. Therefore once a few foundation units have been completed the simulation can be executed in order to determine the feasibility of moving a facility to a more suitable location.

An example of a possible trade-off might be to determine whether it is more feasible to install a secondary facility of a specific type, rather than to increase the number of supply trucks operating from that facility. The previously mentioned decision will decrease the average transfer time of resources on site for that specific operations, in return resulting in an operation that is performed more effectively and at a higher productivity. Such decisions may also reduce the level of congestion on site, since an operation is now deployed from multiple destinations rather than from a single point where all trucks have to return to.

The decision variables influence the objective functions of the SLP model. There are multiple objective functions (i.e. time and cost) designed to give an indication of the effectiveness of both the site layout and material supply. The formulation of the cost and time objective functions are discussed in the next section.

4.7.3   Objective functions

The objective function includes the capital cost of installing construction facilities and also the transportation cost of travel on site. However, there are multiple objectives and therefore construction managers must also take into consideration the time it takes a facility to supply

all of its demand locations and the average transfer time of resources on site. Managers must look at all these results when performing various trade-offs to design an optimized construction deployment strategy. These multiple objectives were kept separate, and not weighted to deliver a single answer in terms of both time and cost. Thus there are various objective functions which are analysed separately. The first is cost, and the second time, and they are discussed below. However, since the model is an interactive management system that allows the user control over the proceedings and provides the user with a visual of the 2D construction site, the user can design the site layout to meet various practical objectives.

Cost objective function

The cost objective function (Eq. (4.3)) is implemented to minimize the total travel cost on site (handling cost), also taking into consideration the installation/establishment cost of construction facilities.

In the present model the travel cost (CT_{ij}) is designed to consider the frequency of travel (f_{ij}) between facility (i) and foundation (j); the time of traveling (t_{ij}) between the two destinations and cost rate (C_r) per minute for traveling between two destinations.

For example, the travel cost for traveling between a batch plant and a single foundation unit can be identified based on Eq. (4.4). The estimated parameters have been identified through an interview with the resident engineer on the SKA project (Dawie Le Roux, see Appendix A). However, they can be accessed and changed at any time.

First, the frequency of travel (Eq. (4.5)) depends on (1) the type of facility and characteristics which in the example is trucks capacity of 6m³ (V_{truck}); and (2) the quantity (Q_s) of concrete that is required at a foundation site, estimated to be 72m³. Accordingly it is estimated that concrete delivery will require 12 round trips (i.e. f_{ij} = 24 one-way trips) to transport the total concrete demand quantity at a single foundation site.

Second, the time of travel is estimated using Eq. (4.7) which includes the following parameters: (1) the Manhattan distance between the two destinations; (2) the maximum truck speed; (3) and then a conversion factor to obtain the answer in minutes. In order to check time constraints on site, distance is expressed in terms of time.

Third, the cost of travel is calculated using Eq. (4.9) which includes the constant fuel cost rate Eq. (4.10) and the hiring cost of the construction vehicle Eq. (4.11). Eq. (4.10) includes the following parameters: (1) the average truck speed on SKA estimated to be 40km/h; (2) truck fuel consumption identified as 3km/litre; and (3) the cost of fuel estimated at R10/litre. Thus, according to Eq. (4.10) the fuel cost rate is estimated to be R 2.2/min. This rate is assumed to

remain constant, and can be changed at any time by the user by updating the assumptions in (1), (2) or (3) above. Eq. (4.11) simply includes the hiring cost per minute of the construction vehicles operating from the respective temporary construction facilities. This parameter can be specified by the user for all the respective construction facilities on site.

If transportation from a different type of facility is considered, such as a site camp, the frequency of travel (Eq. (4.6)) depends on: (1) the number of visits (Q_v) per day; and (2) the duration of construction (D_f) at the foundation unit for which visits are required. In the example it is estimated that a foundation unit must be visited twice every day by a foreman from a site camp for the entire duration of the construction of the foundation unit. Accordingly, it is estimated that 2 round trips (i.e. f_{ij} = 4 one-way trips) will be made to a single foundation unit.

$$\text{Minimize:} \quad \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J}\left[k_{ki}y_{ki} + CT_{kij}x_{kij}\right] \qquad \boldsymbol{R} \qquad (4.3)$$

$With$:

$$\text{Travel cost:} \qquad CT_{kij} = \left[(f_{ij})_s OR\ (f_{ij})_v\right] \times t_{ij} \times C_r \quad for\ k \qquad \boldsymbol{R} \qquad (4.4)$$

$$\text{Travel frequency:} \quad Supply: (f_{ij})_s = \frac{Q_s}{V_{truck}} \times 2 \qquad (4.5)$$

$$\text{Travel frequency:} \quad Visit: (f_{ij})_v = \frac{Q_v}{day} \times D_f \times 2 \qquad (4.6)$$

$$\text{Travel time:} \qquad t_{ij} = \frac{d_{ij}}{MaxTruckSpeed} \times 60 \qquad \boldsymbol{min} \qquad (4.7)$$

$$\text{Travel distance:} \qquad d_{ij} = |X_i - X_j| + |Y_i - Y_j| \qquad \boldsymbol{km} \qquad (4.8)$$

$$\text{Travel cost rate:} \qquad C_r = (C_{fuel} + C_{vehicle,k}) \qquad \frac{\boldsymbol{R}}{\boldsymbol{min}} \qquad (4.9)$$

$$\text{Fuel cost rate:} \qquad C_{fuel} = \frac{Max\ truck\ speed}{60} \times \frac{Fuel\ cost}{Fuel\ consumption} \qquad \frac{\boldsymbol{R}}{\boldsymbol{min}} \qquad (4.10)$$

$$\text{Vehicle hire cost:} \qquad C_{vehicle,k} = \frac{Vehicle\ hire\ cost\ (R/hour)}{60} \qquad \frac{\boldsymbol{R}}{\boldsymbol{min}} \qquad (4.11)$$

The following constraints indicate that: (4.12) implies that a demand is only supplied by one source and goes along with (4.13) where a facility either delivers the demand or does not. The y_{ki} term ensures that the cost is considered only once a facility i of a specific type k is realized in the model. The values of x_{kij} and y_{ki} are easily defined as part of the input, being either =1, or = 0, and ensures a smooth approach towards the programming of the cost objective function. The time constraint shown in (4.14) ensures that no demand can be supplied by a source if the delivery time exceeds the maximum delivery time imposed on that source.

$$Subject\ to: \quad \sum_{i\in I} x_{ij} = 1 \quad j \in J \tag{4.12}$$

$$x_{kij}\{0,1\} \text{ and } y_{ki}\{0,1\} \quad \text{with} \quad y_{ki} \geq x_{kij} \tag{4.13}$$

$$t_{ij} \leq t_{max} \tag{4.14}$$

Where,

CT_{kij} = The total transport costs for supplying all of destination j's demand from source i

f_{ij} = Frequency of one way traveling between source i and destination j

t_{ij} = The travel time from source i to destination j

d_{ij} = Distance in km between source i and destination j

Q_s = Demand quantity of the destination j that must be supplied by source i

Q_v = Demand number of visits to destination j from source i

D_f = Duration of construction at destination j

C_r = Travel cost rate to express the travel time in terms of cost

C_{fuel} = Constant fuel cost rate

$C_{vehicle,k}$ = Vehicle hire cost rate dependant on the vehicle operating from source i of facility type k

K = Set of different types of construction facilities on site

I = Set of sources of each facility type k on site

J = Set of demand destinations on site

x_{ij} = The proportion of destination j 's demand satisfied by source i

y_{ki} = A factor where cost is only considered when source i of facility type k is realised in the model

k_{ki} = Fixed cost of establishing source i of facility type k

Time objective function

In the SLP model a time objective function was designed to provide answers related to material handling time and resource traveling time on site. However, this function calculates travel time differently for a supply demand than for a visit demand. For example, in the case of a batch plant that delivers a "supply" demand, the total time it will take for the batch plants to deliver to all 190 foundations will take roughly 124 days, at an average time of 3.22 hours per foundation (see Table 4.4). In the case of a storage yard that delivers a "visit" demand, it is calculated that the average transfer time from the storage yard to a foundation unit will be roughly 2.91 hours per day (see Table 4.5).

However, for both these cases the time objective function is also calculated for the individual sources that belong to the respective Facility types. The calculation is made using the foundation units in the *Delivery*-set[1] of the individual sources. This can be seen in Table 4.4 and Table 4.5. An example of the simulation output in the eclipse console can be seen in Table 6.1 and Table 6.2.

The average time a facility takes to deliver the supply demand of all delivery locations (Foundation unit) is calculated with Eq. (4.15). First, the total time of travel from source i to supply to all delivery point destinations (j) in its *Delivery*-set is calculated. Second, it is divided by: (1) the average amount of time available per day on site for delivery (i.e. 5 hours[2]); and (2) 60 to convert the value from hours to minutes. The total serve time ($t_{served,j}$) for supplying all of destination j's demand from source i, is estimated using Eq. (4.22). Eq. (4.22) assumes that there will be no queues (i.e. no idle time) and considers the loading time, unloading time, number of cycles and the time the last truck in a cycle is behind the first truck.

The average transfer time from a visit facility to all destinations (Foundation unit) is calculated with Eq. (4.16). First, the total time of travel from source i to visit all the delivery point destinations (j) in its *Delivery*-set is calculated. Second, it is divided by: (1) the total number of visit destinations; (3) and (2) 60 to convert the value from hours to minutes. The total transfer time ($t_{transfer,j}$) for visiting all of destination j's demand from source i, is estimated with Eq. (4.23). However, note that the number of cycles for a supply facility (C_{numV}) is calculated differently from a visit facility (C_{numS}).

Time :	*Supply*: *Time*:	$\dfrac{\left[\sum_{j\in J} t_{served,j}\right]}{60 \times 5}$	*days*	**(4.15)**
Time :	*Visit*: *Time*:	$\dfrac{\left[\sum_{j\in J} t_{transfer,j}\right]}{J \times 60}$	*time/day*	**(4.16)**

$$With:$$

Round trips:	$e_{round} = \dfrac{f_{ij}}{2}$		**(4.17)**
Number of cycles:	*Supply*: $C_{numS} = \dfrac{e_{round}}{n_{truck}}$		**(4.18)**
Number of cycles:	*Visit*: $C_{numV} = \dfrac{Q_v}{n_{truck}}$		**(4.19)**

---

[1] The demand destinations on site which is the closest to a particular facility for the supply of a specific demand.

[2] On the SKA project concrete is only cast in the morning and afternoon, since it is too hot during the midday

Cycle time:	$t_{cycle} =$	$t_{load,i} + 2 \times t_{ij} + t_{unload,i}$	**(4.20)**
Last truck behind:	$if(n_{truck} > 1)$ $t_{behind} =$	$(n_{truck} - 1) \times t_{load,1}$	**(4.21)**
Supply finish time:	*Supply*: $t_{served,j} =$	$t_{cycle} \times C_{numS} + t_{behind}$	**(4.22)**
Visit finish time:	*Visit*: $t_{transfer,j} =$	$t_{cycle} \times C_{numV}$	**(4.23)**

With:

$t_{served,j}$ = The time required to supply all of destination j's demand from source i

$t_{transfer,j}$ = The transfer time to visit destination j's from source i a specific number of times.

f_{ij} = Frequency of one way traveling between source i and destination j

e_{round} = Frequency of round trip traveling between source i and destination j

C_{numS}, C_{numV} = Number of round trip cycles between source i and destination j

t_{ij} = The travel time from source i to destination j

t_{cycle} = The cycle time from source i to destination j

$t_{load,i}$ = The loading time of a truck from source i to destination j

$t_{unload,i}$ = The unloading time of a truck from source i to destination j

t_{behind} = The time the last truck in a cycle is behind the first truck

J =The *Delivery*-set containing the delivery points to which source i must supply

j =The delivery points in the *Delivery*-set of source i

As an example an extraction of the results on the fictitious project described in Chapter 7 is used to illustrate the logic of the output.

Table 4.4: Time objective output to supply the demand

Batch plant	Number of units	Total delivery time (days)	Material handling time (hours/f)
1	99	67	3.35
2	92	57	3.08
Summary:	191	124	3.22

f = antenna foundation unit

Table 4.5: Time objective output for visit demand

Storage yard:	1	2	3	4	5	6	Summary
Number of units	6	59	61	48	7	10	191
Time (hours/day):	5.2	2.53	2.75	2.43	4.46	5.94	2.91

Thus, if the results from the time objective are undesirable (too long), an additional storage yard can be positioned on site in order to reduce the transfer time associated with a storage

yard. The same principle applies to the batch plant example. However, if the two batch plants in Table 4.4 were to operate simultaneously, the total delivery time would decrease to 67 days. The travel time on site can also be reduced by increasing the number of construction vehicles operating from the respective construction facilities. As has been mentioned, these variables can be optimized by the construction manager.

4.7.4   Additional functionalities for SKA

Determining the delivery set of a construction facility

This is the functionality that makes it clear which foundation units, and how many, belong to each of the construction areas in the case where a decentralized construction area is selected (see §2.2.1). The demandObject of a specific foundation unit is assigned to a supplier during the execution of the algorithm that calculates the minimum supply time amongst multiple sources for that specific demand (see Figure - B.2). It is here where that foundation unit is added to the delivery set of the construction facility that can support the delivery the quickest (i.e. multiple storage yards or site camps).

Estimating batch plant truck requirement

Another functionality is estimating the trucks' requirements to deliver concrete from a Batch plant to an antenna foundation unit. The number of trucks required to effectively deliver material is calculated with Eq. (4.24) to (4.26): (Lafarge, 2015)

$$Calculating\ number\ of\ trucks: \qquad N_{ij} = \frac{t_{cycle}}{t_{unload,i}} \qquad\qquad (4.24)$$

$$Calculating\ number\ of\ Loads: \qquad L_{ij} = \frac{Q_s}{V_{truck}} \qquad\qquad (4.25)$$

$$Lower\ of\ the\ two: \qquad N_{ij} = minimum\{N_{ij}\ ; L_{ij}\} \qquad\qquad (4.26)$$

The equation (4.24) calculates the number of trucks to be batched for the project before the first truck has returned for its second load. After that point, no more trucks will be needed. The equation also assumes that, as one truck finishes unloading, another is just arriving at the antenna foundation unit. This application can be used to improve the concrete supply operation on site and to overcome the challenge of slow concrete delivery as experienced in the MeerKAT project (refer §2.3.5).

4.7.5   Simulation algorithm outline

The simulation-based algorithm (outline is shown in Figure 4.8), executes in two loops and contains 2 sub-processes. The outer loop iterates over all the construction facilities created by the user and the inner loop iterates over all foundation units on site. The subprocesses

include: (1) the calculation of supply times of deliveries from source to foundation units; and (2) the selection of a supplier for a specific demand. It is this algorithm that initializes the dynamic flow of material-handling equipment on site.

Below is a list of descriptive steps on how the execution of the simulations algorithm is implemented.

Step 1: The simulation starts by retrieving the list of facilities from the site model.

Step 2: Once a *Facility* object has been retrieved a check is performed to determine whether a *Foundation* contains the demand supplied by that particular *Facility* and also whether the facility exists on site.

Step 3: Compute time matrix: If the previous step is true, the algorithm proceeds to a sub-process where the supply times for all the sources that can supply that demand is calculated and added to that foundation unit (refer to Figure 4.7 for a graphical illustration and Figure - B.1 in Appendix B for algorithm outline).
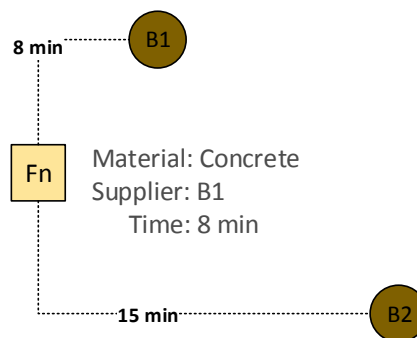
Figure 4.7: Compute Time Matrix

Step 4: Get minimum time: For each of the foundations the supply times from sources for a specific demand is known. The algorithm then proceeds to another sub-process that determines which source can supply the demand the quickest (refer Figure 4.7). That source is then assigned as the supplier of that demand for that foundation unit (refer to Figure - B.2 in Appendix B for algorithm outline).

Step 5: A time constraint is then performed to check the Deliverability of that DemandObject. Deliverability refers to a value that is either true or false and indicates if the delivery satisfies the time constraint.

Step 6: If the demand object satisfies this constraint the transportation cost is calculated and summarised.

Step 7: The algorithm then iterates to the next *Facility* and repeats the optimization for the next facility.

Once the algorithm has executed, the total cost is calculated and also all the information calculated in the process is stored and kept available in the *Facility*, *Sources* and *DemandObject*-objects.
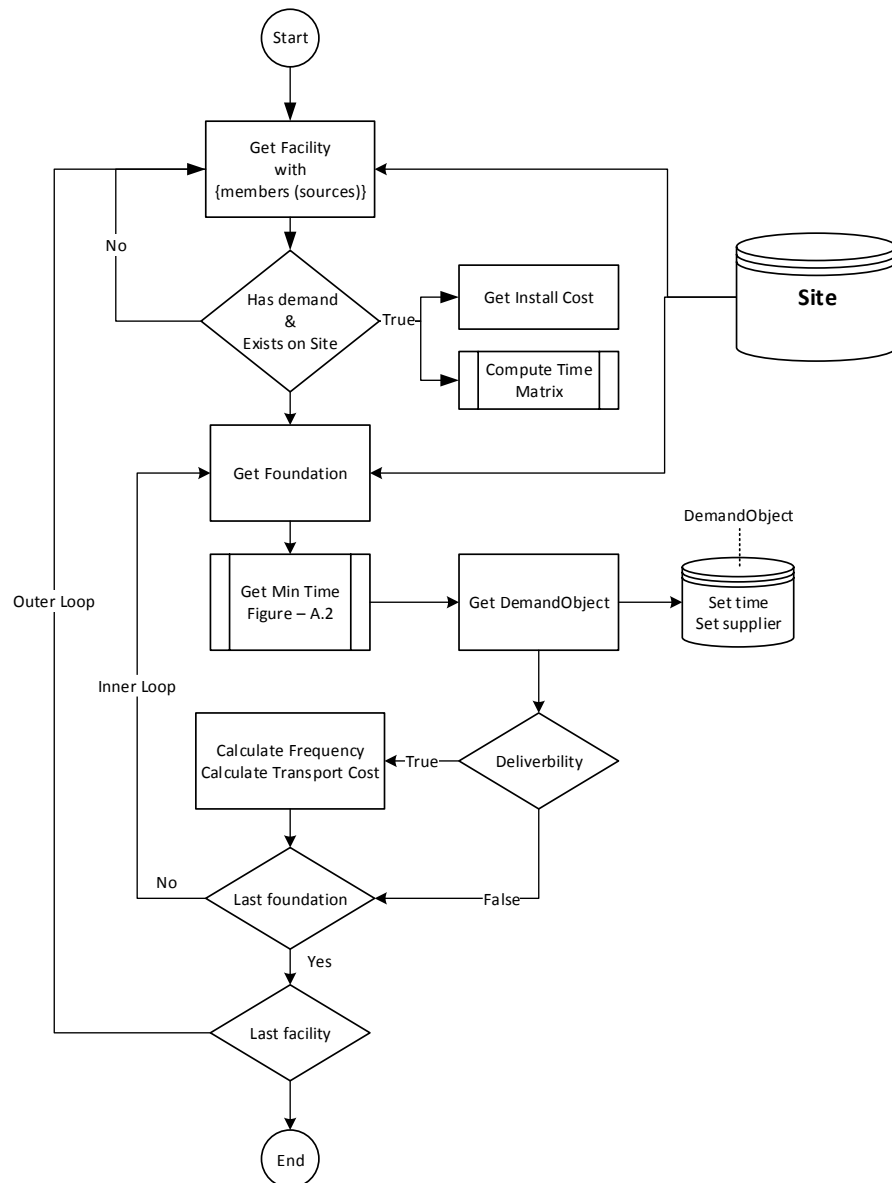
Figure 4.8: Simulation Algorithm outline

4.7.6 SLP model validation

In order to show that the simulation algorithm executes correctly and to validate the calculations discussed in §4.7.3, an example including 8 foundation units are used. The following calculations are shown in Appendix B in the Table reference shown in the right hand column:

1.	*the travel time between sources and demand destinations*	Table - B.1
2.	*appointing supplier with minimum supply time*	

3.	*the transport cost from supplier to demand destination*	
4.	*the round trip cycle time of both supply demand and visit demand*	Table - B.2
5.	*the total time of delivery (Supply finish time) or travel (Visit finish time)*	
6.	*the truck requirements for a batch plant*	Table - B.3

It was found that the simulation algorithm executes and performs the calculation listed in §4.7.3 correctly. The use of the model will be shown in CHAPTER 7 during the implementation of the model on a fictitious SKA project.

4.8   Automatic Optimization consideration

As mentioned previously, the present SLP simulation model will serve as framework for future development. The model may be extended to an automatic optimization framework which considers the relocation of facilities at various construction stages as a decision variable. Therefore such an application will be briefly discussed here in terms of the model formulation, decision variables and geometrical constraints. However, an optimization framework in essence consists of a state vector that contains the decision variables representing the system. The simulation-based framework then executes using these decision variables and quantitatively measures the effectiveness of the decision variables included in the state vector. The different metaheuristic techniques in fact differ in the way that they intelligently manipulate the decision variables in the state vector in order to find the state vector that delivers a near-optimal solution. An objective metrics must be designed which enables the quantification and minimization of the site layout cost (Said, 2010). In order to develop such an extension the following must be incorporated in the implementation:

Model Formulation: It should be identified which facilities are positionable in each construction stage that includes 1) all movable facilities that continue on site from the previous stage; (2) all new movable and stationary facilities that are used for the first time in this stage. Therefore it is proposed to follow the concept as carried out by El Rayes & Said, (2009); Said, (2010), where construction facilities in the model have been classified into three main categories: fixed, moveable and stationary. This concept will be essential during the automatic optimization of the site layout:

1. Fixed facilities: These are predetermined, fixed positions that planners do not need to select locations for. In an ordinary project, these locations might for example be the location of the constructed building or access roads;
2. Stationary facilities: These are temporary facilities of which construction planners only have to select the location once. Due to their high installation cost, it is not feasible to relocate them over the project duration; and

3. Moveable facilities: These are temporary facilities that can be repositioned at the start of any of the identified construction stages. Examples include site camps, storage areas, fabrication areas etc.

Geometrical constraints: The positioning of any temporary facility on site must be subject to a set of geometric constraints as discussed in section §4.5.2 (El Rayes & Said, 2009; Said, 2010; Zouein & Tommelein, 1999; Easa et al., 2009). The development of a constraint-checking algorithm that evaluates the feasibility of positioning a temporary facility and reporting any violations is required. This can be the development of future work.

However, with regards to manual optimization, two SLP model extensions have been developed which will be discussed in the next section. The integration of these extensions to the SLP model, however, still requires more work.

4.9   SLP Model Extension

In this section two optimization extension models, developed for the SKA project, are described. They have been developed to cater for specific requirements on the SKA site. These extensions include: (1) location optimization model; and (2) transportation problem optimization model.

4.9.1   Location optimization extension

Once the set of delivery points for each source is known it might be desirable to know the optimum location that delivers a minimum travel distance to all of the foundations in the set. Since the travel distance will be at a minimum, handling cost and time on site will be reduced and in return will result to a more effective site layout.

For example, it might be necessary to determine a location on site where material for construction can be borrowed (i.e. sand). Due to the large construction area of SKA it becomes desirable to know the best possible location where one can start searching for feasible borrow pits. Hence an optimization extension was developed for the model whereby a location can be determined which results in minimum travel distance to all of the delivery destinations that require material from the borrow pit. The extension is discussed in more detail below.

Possible site locations are generated based on a grid of locations that depends on a grid pitch defined by planners (see Figure 4.9). The best position is then found by means of evaluating all possible alternatives and selecting the best one. The grid represents the decision space of the enumeration process. For example, the decision space in Figure 4.9 will include 25 possible locations. Therefore planning precision and the quality of the location solution is improved by decreasing the grid pitch. The same can be done when two destinations are to

be determined. The method then computes two locations which deliver the minimum distance to all destinations.
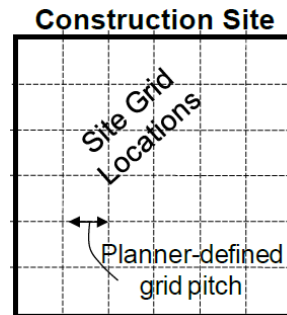
Figure 4.9: Site grid locations (El Rayes & Said, 2009)

This extension is supplemented with another extension that has been designed for the SKA project, which will be discussed in §4.9.2 below.

4.9.2   Transportation problem extension

The optimization principles that apply to this extension are those of the transportation problem as described in §3.3.4. In order to discuss the practicality of this extension to the SKA project, the scenario described in §4.9.1, entailing the determination of the location of a borrow pit on site, is elaborated upon.

In this example, it can be argued that once the best possible location is found, it is not to say that sufficient material will be borrowed at this location. Moreover, it might be found that in the vicinity of this optimal location, four borrowing locations each have a quantity of material to be borrowed (such as described in §3.3.4). In this case it must be determined what quantity of material from each borrow pit must be transported to each demand destination in order to minimize the transport cost. Therefore a transportation optimization extension was developed for SKA. Discussed below is a brief description of how the transportation method is formulated.

Implementation

The objective function is shown in Eq. (4.27). The aim is to determine the decision variables (x_{ij}) of the objective function which minimizes the transport cost. The optimum solution is the values x_{ij} that minimize the overall cost transporting from source i to destination j. The various methods available to solve the problem was discussed in §3.3.4. The model is formulated as presented below and was implemented using the Minimum cost method. Figure 4.10 shows a graphical network representation of the transportation problem.

$$\text{Minimize:} \quad \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} \qquad \qquad \textbf{(4.27)}$$

$$\text{Subject to:} \quad \sum_{j=1}^{J} x_{ij} = S_i \qquad \qquad \boldsymbol{i \in I} \qquad \textbf{(4.28)}$$

$$\sum_{i=1}^{I} x_{ij} = d_j \qquad \qquad \boldsymbol{j \in J} \qquad \textbf{(4.29)}$$

$$\text{and} \quad x_{ij} \geq 0 \qquad \qquad \boldsymbol{for\ all\ i\ and\ j} \qquad \textbf{(4.30)}$$

With: c_{ij} being the unit transportation cost for transporting the units from source i to destination j, x_{ij} is number of units shipped from source i to destination j, S_i is the number of supply units available at source i, d_j is the number of demand units required at destination j.
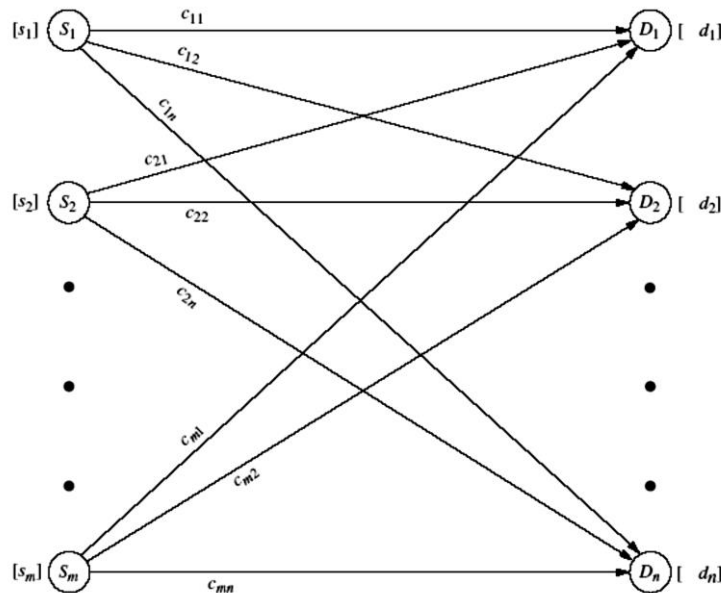
Figure 4.10: Network representation of the transportation

It is said that the transportation problem is balanced if the total supply from all sources equals the total demand of all destinations. In the case where it is unbalanced, the total material available for supply exceeds the required demand. A dummy site is then invented that will receive the excess of which the transport cost from supplier to site is zero. In essence the material is never moved at all.

$$\sum_{j=1} S_i = \sum_{i=1} d_j$$

4.10 Summary

This chapter presented the development of a prototype site layout planning system (SLP model) that facilitates the manual optimization of site layout planning and on-site material supply. The model utilizes a simulation-based framework which makes it possible for construction managers to perform a series of "what if" analyses in order to optimize the site layout. The SLP model can be used as a decision-making tool to aid construction managers in minimizing the site layout cost and total site transportation time. However, since the model is designed as an interactive management system, the human judgement and experience of an expert who understands the complicated process of designing a site layout is captured. Therefore the model can be used to achieve user specific objectives. The components addressed in this chapter can be summarised as follows:

1. *Design generic temporary construction facility* (batch plant, storage yard etc.)
2. *Make it possible to add more than one facility (source) on site (i.e. two storage yards)*
3. *Create demand locations on site containing the necessary attributes*
4. *Design demand location to have multiple material and resources requirements*
5. *Connect sources and demand destinations in a continuous 2D space*
6. *Simulate material and resource flow between sources and demand destinations*
7. *Design practical resource flow constraints*
8. *Design cost and time objective functions*
9. *Consider resource transporting and material handling construction vehicles*
10. *Make it possible for user to design and customize site layout*
11. *Estimate travel distance using Manhattan distance*
12. *Consider material handling and resource traveling equipment*
13. *Make it possible to change decision variables*
14 *Formulate the integration with repetitive project scheduling (RPS) model*

The SLP model is formulated in order to support the integration with the repetitive project scheduling (RPS) model (refer to Figure 10.2). The possibility of enhancing the model to have automated functionalities was discussed in terms of model formulation and geometric constraints. This type of functionality can be used to guide the user through the proceedings of planning the site layout. Because of the need for achieving multiple objectives in this research study, the SLP model is incorporated in the other research task of this study to develop a Repetitive Project Scheduling (RPS) model.

CHAPTER 5

REPETITIVE PROJECT SCHEDULING (RPS) MODEL

5.1 Introduction

The objective of this chapter is to develop an interactive repetitive project scheduling (RPS) model that can be used by a construction manager for the purpose of manually optimizing the project schedule with respect to multiple and conflicting objectives. The objectives of the present model are to (1) find the minimum project duration; and (2) deliver a project schedule that maximizes the resource utilization by reducing or managing the undesirable resource interruption that causes non-productive crew idle time.

5.2 Overview on Repetitive Project Scheduling

In this section an overview of the theory and graphical representation of scheduling repetitive projects will be discussed, in order to give the reader a better understanding of the problem at hand and to understand the theory that follows. Accordingly, this section gives an overview on the (1) logical sequence of repetitive units; (2) precedence relationship between activities to ensure job logic constraints; and (3) resource consideration. The scheduling procedure may in fact be considered as the balancing of activity production lines to reduce crew idle time.

5.2.1 Precedence relationship between repetitive units and activities

First of all it is necessary to determine a logical sequence which the construction of repetitive units need to follow in order to define their pattern of repetition. This sequence can either be accepted as a natural occurrence or may be established to meet the requirements of some production need. For example, in the case of vertical construction projects, the repetitive units are usually discrete entities, such as houses, stores, apartments, or floors in high-rise construction, and work progress is measured in units completed. Similarly, on horizontal construction projects such as highway sections of road may follow in the natural numerical order from project start to project finish (Harris & Ioannou, 1998).

Secondly, it is necessary to identify the precedence constraints among the activities in each unit (Harris & Ioannou, 1998). The number of activities in the network for a repetitive unit is not particularly important and is determined by the nature of the unit.

There are two types of resource constraints that need to be considered, namely resource availability constraints and resource continuity constraints. Availability constraints indicate the limited number of resources available at a specific time to perform the activities, and controls

the output of those activities. Continuity constraints ensure that resources, such as crews, perform work continuously and without interruption for the entire time that they are on site (Jun, 2010).

5.2.2   Resource consideration

Most activities require a number of resources (i.e. equipment needs and operator) and it is assumed that a group of resources is associated with an activity. Therefore a crew consists of both labour resources and equipment resources. It is also assumed that the same resource (crew) will be used for like activities in successive repeating units, therefore each activity's resource remains consistent from unit to unit. For example, if an activity in the first unit requires a crew of concreters, that activity in each succeeding unit will require the same crew of concreters. For each repetitive activity a duration for completing one unit is estimated, and is typically obtained from the quantity (Q) of work and the associated resource production rate rpr of the crew performing the activity. The estimation can also be obtained from the Pert formula that entails a three point estimate. The (rpr) is directly proportional to unit production rate (upr), which is the slope of a production line in an RPS model. For example, if the rpr is expressed in square meters per day (m^2/d) and the Q in square meters per floor (m^2/fl), then the (upr) is in floors per day (fl/d).

The idle time of a crew is considered as the duration of time in which a crew performs no work during their employment period, i.e. getting paid but not producing any output. Idle times in repetitive activities can be categorised into two different types, the first being the work interruption between units and the second the time of arrival at units. The sum of these two types of idle times for a resource is the total "Crew idle time" (Srisuwanrat, 2009). Therefore in order to reduce or eliminate the idle time, resources must be incorporated into the schedule. How activities are scheduled to eliminate crew work interruptions will be discussed next.

5.2.3   Converging production lines

In order to illustrate the conversion from a bar chart to a production curve, Figure 5.1 and Figure 5.2 are shown. Figure 5.1 represents a bar chart of a pair of activities, *A₁* and *B₁,* removed from a precedence network drawn for a project's repetitive Unit 1, where precedence relationship between the activities is finish-to-start. The two activities are again plotted in the form of a production curve in Figure 5.2. Activity *A₁* is represented by the inclined line stretching from the start of Activity *A₁* in Unit 1 to the finish of Activity *A₁* in Unit 1.

It is important to note that the second line displayed in Figure 5.2 is converging with the first, due to the upr for activity A₁ being one-third unit per day (1/3 u/d), and for Activity B₁ the rate

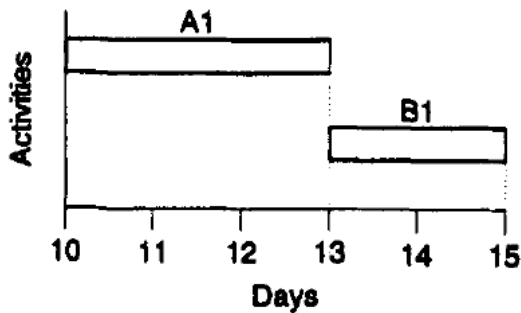is (1/2 u/d). It is clear that the slope of the respective activity production lines represents the *upr*.

Figure 5.1: Activity bar chart plot
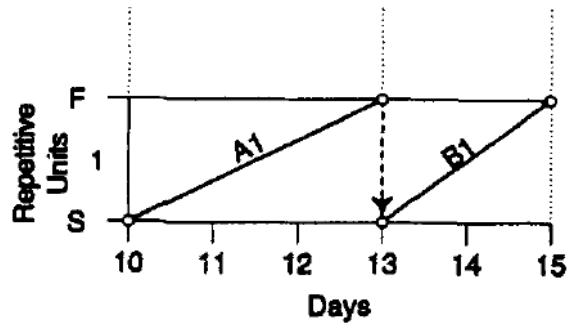
Figure 5.2: Activity production plot

In order to illustrate the balancing of converging production lines the same pair of activities are extended over three repetitive units and plotted in the form of a bar chart in Figure 5.3(a). It can be seen that there is a one day lag between the B activities from one unit to the next, due to the fact that only technical precedence logic is employed. Accordingly, Figure 5.3(b) shows a unit-by-unit production line plot of the same activities with the finish-to-start relationships shown by the downward-pointing arrows.
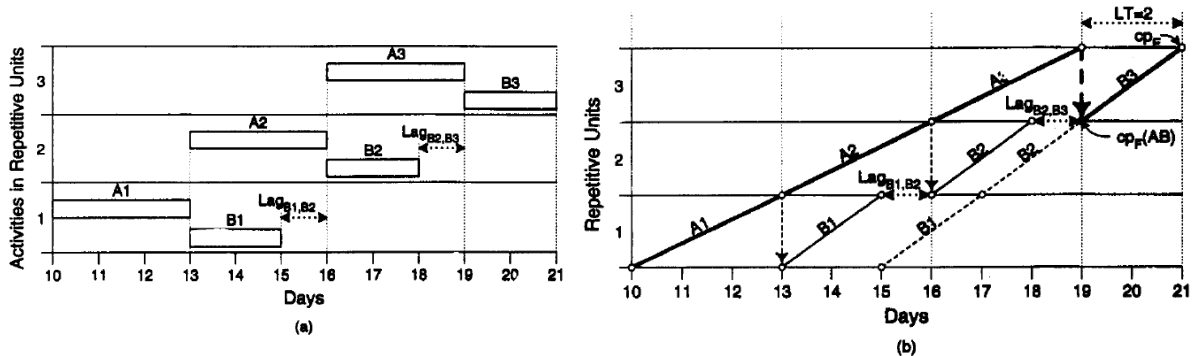
Figure 5.3: Converging production lines (Harris & Ioannou, 1998)

Since it is desirable to make a continuous production line for the *B* activities and provide for the uninterrupted utilization of resources, the start of Activity B_1 must be delayed by two days and the start of Activity B_2 must be delayed by one day. The resulting production line for the *B* activities is shown in Figure 5.3(b) by the dashed line beginning at the end of day 15, continuing through Unit 2 and extending as a solid line through Unit 3 to finish on day 21.

It is important to notice that the two continuous production lines converge toward the finish of Unit 3 because the unit production rate of the *B* line is greater than that of the *A* line. Also note that the finish of Activity A_3 and the start of Activity B_3 are perfectly synchronized at the beginning of Unit 3.

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Thus, when the unit production rate of an activity's production line is greater than the unit production rate of the preceding activity's production line, the two production lines will tend to converge as the number of units increases (Harris & Ioannou, 1998).

5.2.4 Diverging production lines

In order to illustrate the balancing of diverging production lines, Figure 5.4(a) is presented and is similar to that of Figure 5.3(a). However the unit production rate of activity *B* is lower than that of activity *A*. It can be seen from Figure 5.4(b), that the production lines for both *A* and *B* are continuous and ensure the uninterrupted utilization of resources even though no effort was made to achieve resource continuity.

It is clear that the two unit production lines diverge, therefore, in order to shorten the project duration, the production rate of activity *B* must be increased. Accordingly, suppose that the crew for each *B* activity of Figure 5.4 is increased by 50%, then the change reduces each *B* activity duration so that the unit production rate is the same as that of each *A* activity. Accordingly, the revised unit production rate is shown in Figure 5.4(c), along with the dashed production line from Figure 5.4(b). Any further increase of the unit production rate of activity *B* will cause the *A* and *B* line to converge.

Thus, when the production rate of an activity's production line is smaller than the production rate of the preceding activity's production line, the two production lines will tend to diverge as the number of units increases.
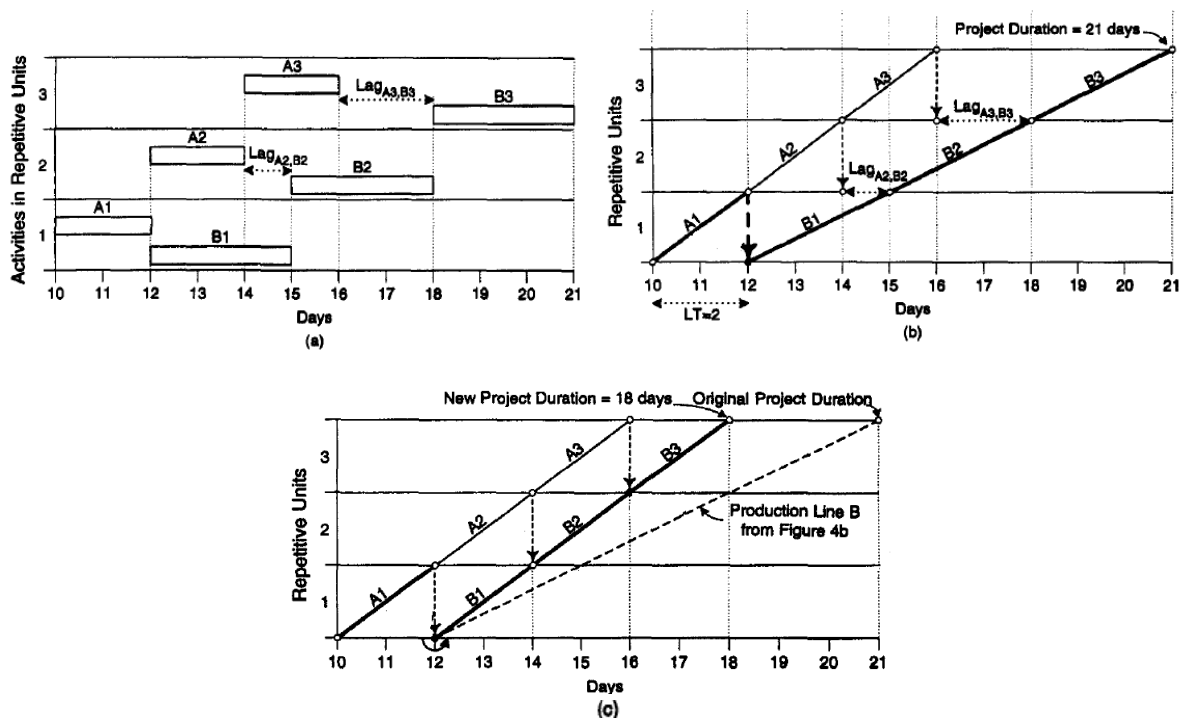

Figure 5.4: Diverging production lines (Harris & Ioannou, 1998)

5.2.5 Typical and non-typical activities

When activities in all repetitive units have the same duration it can be categorised as "typical" repetitive activities (see Figure 5.5 (a)), such as casting the antenna foundations. However, when the repetitive activities don not have the same duration it is categorised as "non-typical" (El-Rayes & Moselhi, 1998), (Srisuwanrat, 2009). In these cases the quantity of work in repeating activities from one unit to the next is not the same (e.g., "Carpeting for Floor 2" may be twice as much as "Carpeting for Floor 1"). In such instances, the upr will vary, depending upon the amount of work in each unit (see Figure 5.5 (b)). SKA is considered as a typical repetitive project, therefore a fixed duration is estimated in the present model and is considered as a fair assumption since the quantity of work remains consistent.
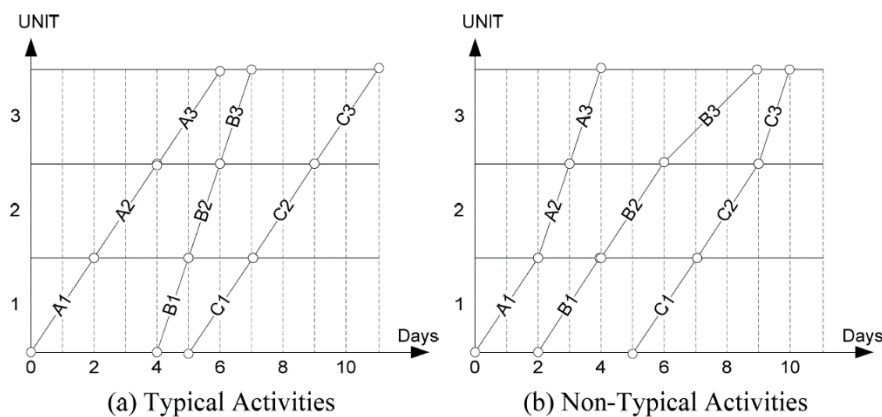
Figure 5.5: Typical and non-typical activities (Srisuwanrat, 2009)

5.3 Model Formulation and Assumptions

The repetitive project scheduling (RPS) model is a manual-based dynamic planning system, integrated with the SLP model, used as a visual communication tool for users to interactively make changes to the construction schedule in order to meet a specific objective.

5.3.1 Repetitive activity consideration

The user is required to identify and determine all activities and their respective construction durations. Activities are defined based on the most significant resources they need for completion. If more than one activity is completed in sequence by the same crew then those activities are grouped together, and completed by that specific resource. This is done since a resource-driven scheduling approach is followed in this study. For example, an activity called "preparing foundation footing" consists of three successive activities (i.e. "cast blinding layer", "steel fixing" and "installing shutters") and all of them can be completed by the same crew in three days. Therefore the crew's unit production rate shall be 1/3 units each day and, as mentioned previously, this is the slope of the production line in the RPS model view (see Figure 6.5).

In the SKA project the quantity of work and material required to complete the construction remains the same from one repetitive unit to the next (refer §5.2.5). This can be similarly assumed in many low cost housing projects (Devi & Ananthanarayanan, 2007). Therefore the activity production rate remains constant over the project duration. The effect of the learning-curve phenomenon where production increases with time was neglected in the RPS model. The model does not consider the beneficial effect of the learning curve. However such an implementation can be seen in Hassanein & Moselhi, (2005).

With regards to the precedence network of a repetitive unit, the scheduling algorithm is only designed to cater for finish-to-start relationships, with or without lag time. Other relationships such as start-to-start, finish-to-finish or start-to-finish were not compensated for. However such an implementation can be seen in El-Rayes, (2001); Hyari & El Rayes. (2006); Liu & Wang, (2012).

5.3.2 Labour crew consideration

With respect to labour consideration in the RPS model, it is assumed that the number of resources assigned to a crew is the most effective formation. Therefore the assignment of any additional resources within that crew will only cause the crew formation to become less efficient and considered to be redundant. Thus it is proposed for this study that when it is desirable to increase the unit production rate of an activity that an identical additional crew should be assigned to the activity. Therefore crews will work on two repetitive units, simultaneously in parallel, and in turn reduce the total duration of these activities in the project. There are not many research developments that consider multiple crews for each task (Bhoyar & Dhananjay, 2015).

The reason for the development of this approach is due to the fact that the repetitive units in the SKA project are discrete and there is no reason why one unit cannot be constructed before the other or in parallel. However, in other construction projects it might not be the same case. For example, if the construction of a three-story building is considered, the first floor must be constructed before the second. Therefore in such a case, in order to reduce the duration, more resources are added to a crew in order to increase the crew productivity rates (El-Rayes & Moselhi, 2001).

Moreover, as mentioned, each of the crews consists of both labour and equipment resources. In order to get an hourly cost rate of a crew it is necessary to distinguish between different resources and to assign rates to each individual resource type. Accordingly, each of the labour resources is assigned a skilled type, i.e. skilled, semi-skilled, basic etc. and for equipment resources the type is also specified i.e. drilling rig, crane, digger loader etc. Therefore the

resource type determines their associated hourly cost rate. The RPS model uses this concept to distinguish between different resource types and to calculate the direct cost of labour. The material cost is calculated on the same basis, where each material type has a cost rate associated with it. The associated cost rates of material and equipment are all variables in the RPS model that can be accessed by the user and changed to accurately estimate the various cost elements.

The indirect cost of crashing[1] activities is neglected, i.e. the additional indirect cost of purchasing an extra laptop for the additional crew that has been assigned to an activity. Thus the result of this assumption is as follows: If an activity takes 10 days for one crew to complete at a direct cost of R10, then it will take two crews 5 days at the same cost of R10.

The model also only makes available one crew option for each activity, which is considered as the most effective crew formation for the specific task. However, as mentioned above, the number of crews assigned to that activity can be increased to reduce the activity duration. Previous developments that have provided the option of various crew formations can be seen in Hyari & El Rayes, (2006) and Hassanein & Moselhi, (2005).

5.4   System Architecture

In this section the architecture of the model in the object-oriented environment will be discussed. The list that follows is a description of the main class objects that form the building blocks of the RPS model. In Figure 5.6 a UML abstraction is illustrated to supplement the explanatory list below. However, the complete UML diagram of the RPS model is shown in Figure - H.1 in Appendix H. The integration of the RPS model and SLP model is also shown in Figure - H.1.

- *Process:* Objects of this class represent a list of activities (tasks) that constitute the repetitive work process completed at each of the repetitive units.
- *Task:* Objects of this class represent a construction activity (i.e. excavation). A *Task* has a duration and a set of predecessor tasks. Accordingly, the early start of a *Task* is calculated to be the latest early-finished of all its predecessors. A Task object also has a "shift" time[2], which is calculated during the initialization of crew work continuity. A *Task* object also has a lag[3] time. Each *Task* is assigned a *Crew* to complete the work and it will complete the *Task* in each repetitive *Process*. The number of *Crew* teams assigned to a *Task* is determined manually by the user in order to obtain the desirable project duration.

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[1] Method for reducing the project duration by reducing the time of one (or more) of the critical project activities to less than its normal activity time.
[2] Postpones activity in order to ensure resource work continuity.
[3] Represents the practical time that is required to pass before the succeeding activities can start. For example concrete has a curing time before succeeding activity can commence.

- *Crew:* Objects of this class represent a group of resources (i.e. labour and equipment) assigned to complete the construction work. A Crew has a specific crew interruption[4] time, which can be assigned a value by the user for the purpose of reducing project duration.
- *Resources:* Objects of this class represent either labour resources (i.e. carpenter) or equipment resources (i.e. crane), that make up the members of a crew formulation.
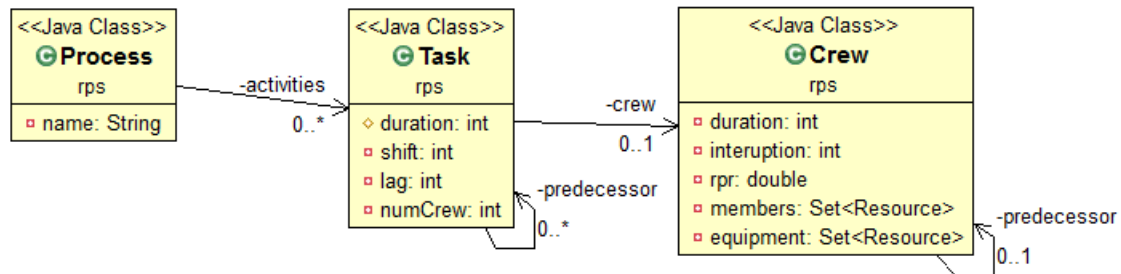
Figure 5.6: RPS model UML diagram abstraction

Table 5.1 lists 7 activities that are included in a repetitive process and shows their precedence relationship. Figure 5.7 is an example of a *Process* object that will be assigned to all repetitive units in the SKA project. As can be seen from Figure 5.7, the process includes the predecessor relationship.

Table 5.1: Predecessor relationship

Task Name	Predecessors
A	-
B	A
C	B
D	B
E	C
F	E and D
G	F
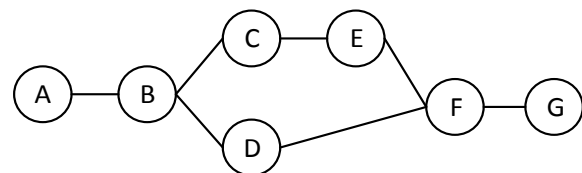
Figure 5.7: Typical repetitive Process-object

5.5   Model Description

The main objective of the RPS model is to develop a model that automatically generates a practical project schedule for the repetitive construction of antenna foundation units, while ensuring crew work continuity and allowing for both specific crew work interruptions and multiple resource crew assignments. The model utilizes a scheduling algorithm to schedule the repetitive construction activities (see Figure - C.2 in Appendix C). The model can also be applied to other projects such as housing projects. The algorithm provides a schedule that complies with the practical scheduling constraints such as job-logic constraints, crew availability and crew continuity, by performing multiple scheduling computations. The

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[4] The specific interruption time that must pass before crew can commence work after the completion of the previous unit.

algorithm also allows for different activities to be performed in parallel. The interactive optimization procedure is described below.

5.5.1   Interactive optimization procedure

The input, execution and output from the model is illustrated by Figure 5.8. As shown, the user is only required to stipulate the type of activities, duration and precedence relationship of one single repetitive process. The model is designed to then compute (1) the scheduled start ($S_{i,j}$) and finish ($F_{i,j}$) dates of construction for each activity (i) in each repetitive unit (j) with zero crew interruptions; (2) the total project duration (D); (3) the total crew work interruption days (R); and (4) total labour cost related to that schedule. The optimization procedure is of a manual nature where the user measures the schedule against the multiple objectives, as discussed in §5.6.5, and makes changes after assessing the graphical production curve project schedule (see Figure 6.5).

The user can increase the number of crews assigned to an activity in order to shorten the project duration. This is typically done for the activity with the longest duration, since its reduction will minimize the project duration.

Another possibility is to assign a crew interruption between repetitive units. In some cases this is advantageous, as discussed in §3.6.4. The model then simulates the changes made and delivers the new project duration and cost. This procedure is repeated until the user is satisfied with the model's output.
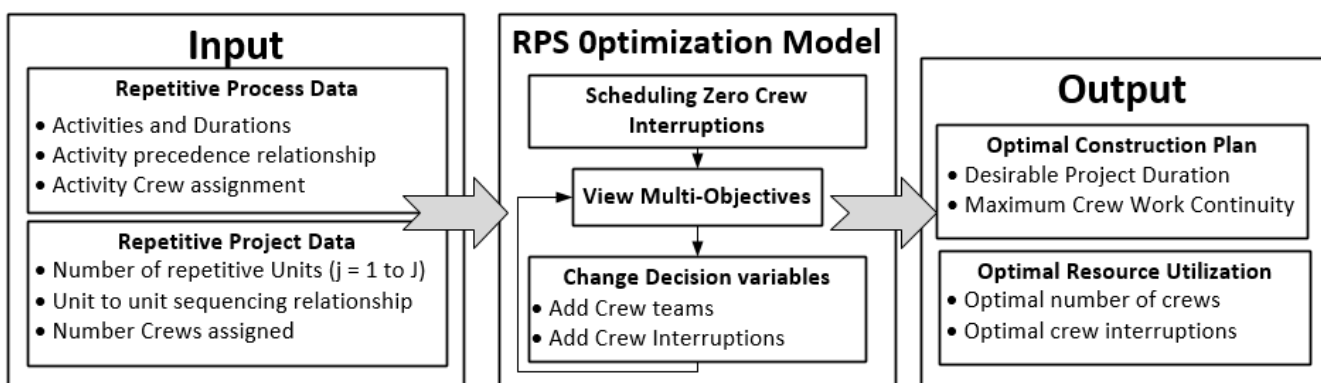
Figure 5.8: Optimization model for scheduling repetitive construction

The model utilizes a repetitive scheduling algorithm that performs scheduling computations similar to developments made by El-Rayes & Moselhi, (1998); El-Rayes & Moselhi, (2001); Hyari & El Rayes, (2006). The section that follows describes the execution of the scheduling algorithm and how the scheduling computations are performed.

5.6 Model 2: Repetitive project scheduling Algorithm

5.6.1 Algorithm execution

The scheduling algorithm is executed in three phases. The first two achieve compliance with the job logic and crew availability constraints, and the third achieves compliance with the crew work continuity constraint. The sequence of construction (*Unit-to-Unit Logic*) from one unit to the next depends on the arrangement of the list of foundation units, received from the SLP model, i.e. drilling in unit one commences before drilling in unit two. The precedence diagram of the repetitive project of the process shown in Figure 5.7 is illustrated in Figure 5.9. Therefore this is not so much a phase at a dependency.
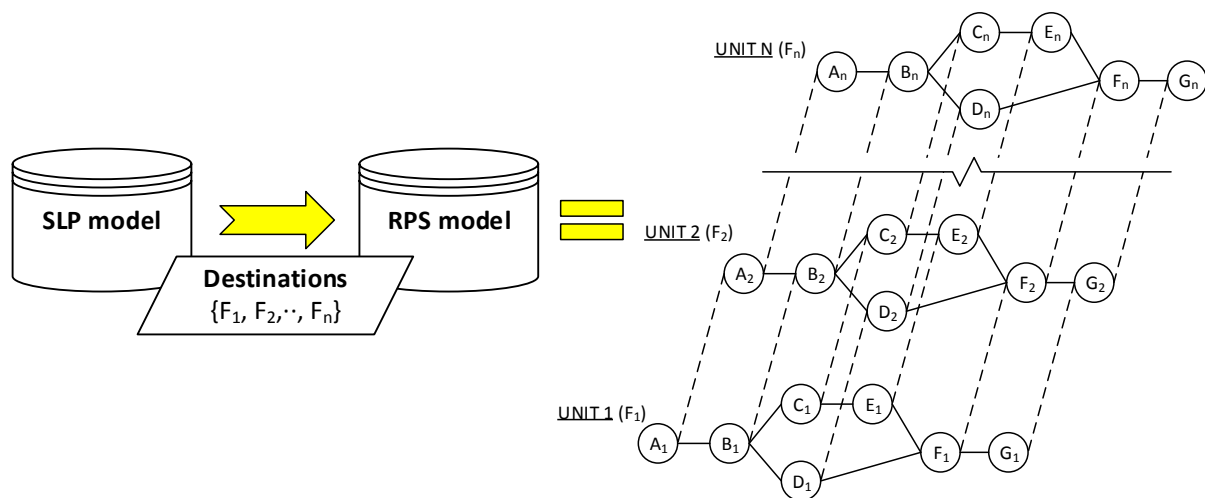
Figure 5.9: A precedence diagram for a repetitive project

The three phases are discussed below and an algorithm outline that shows the execution of all three phases is shown in Figure - C.2 in Appendix C.

Phase 1:Initialize Unit Job logic. Each *Foundation* unit is automatically assigned the process of activities stipulated by the user. As mentioned, the precedence relationship between tasks within the repetitive process has already been defined before it is assigned to all the units, (see Figure 5.7), therefore once phase 1 has been completed, each foundation unit has a process with the proper activity job-logic within its process. Thus in this step the early start $S_{Logic[i,j]}$) and finish ($F_{Logic[i,j]}$) dates for activity (i) in unit (j) are calculated that satisfy job logic at a repetitive unit level.

Phase 2:Set Crew Availability Constraint. This constraint ensures that in order to start the "drilling" activity in unit two, the "drilling crew" must first have completed the drilling in unit one. Therefore in this phase the precedence logic of crew work flow is assigned to all tasks. It is this phase that ensures that crews are available to perform work. Thus in this

step the early start ($S_{Crew[i,j]}$) and finish ($F_{Crew[i,j]}$) dates for activity (i) in unit (j) are identified that satisfy crew availability constraints at a project level.

Phase 3: Set Crew Work Continuity Constraint: In this phase tasks are scheduled to ensure crew work continuity; to ensure that crews are not interrupted due to the imbalance of production rates between crews. The scheduling is performed by calculating a shift value that will deliver crew work continuity.

The scheduling computations implemented in the execution of the phases listed above, are explained in the next section.

5.6.2   Scheduling computations

The description of the scheduling computations is supplemented with the graphical illustration in Figure 5.10. The calculation of the early start and finish times for activity (i) in repetitive unit (j) are similar to ensuring job-logic and crew availability, but the precedence relationship they use is different. For example, job logic constraint requires (red line in Figure 5.10) that activity i (e.g. foundation) can only start after the completion of its predecessor activity $i-1$ (e.g., excavation) in each repetitive unit (j). Crew availability constraints (green line in Figure 5.10) require that activity i (e.g. foundation) in repetitive unit (j) can only start after the completion of its predecessor activity i (e.g. foundation) in repetitive unit ($j-1$).
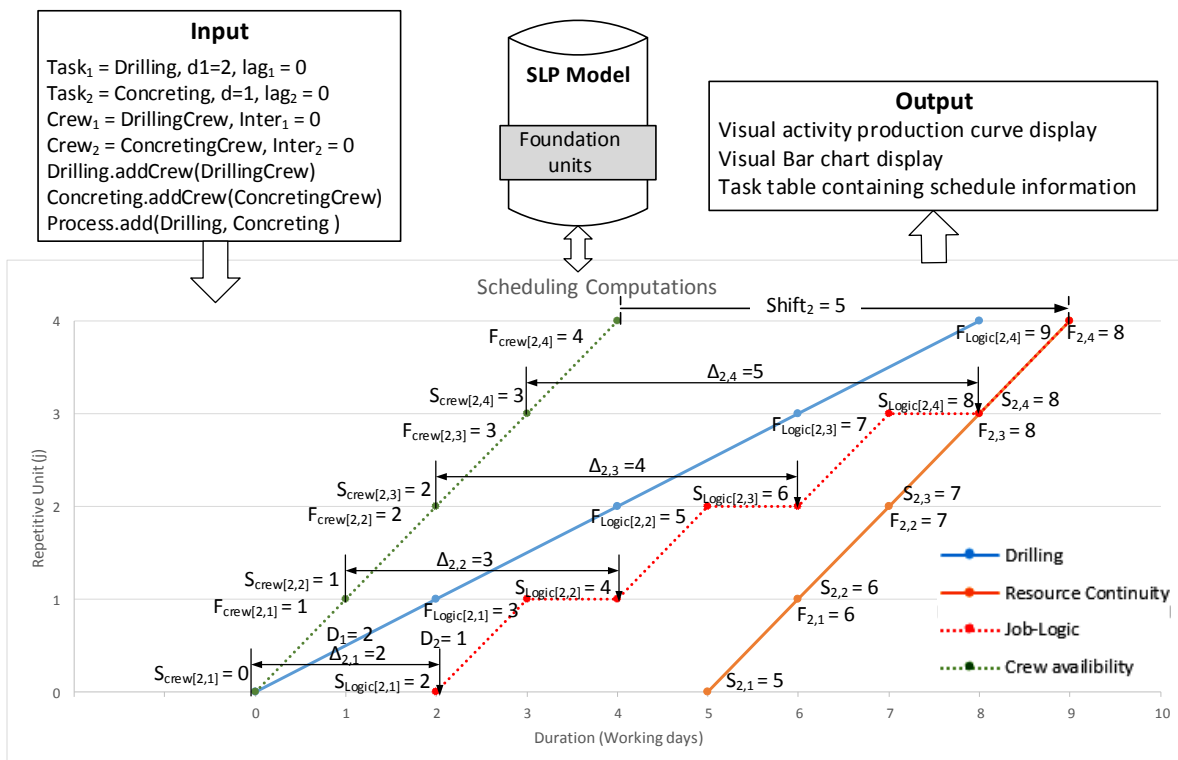

Figure 5.10: Scheduling computations for "concreting" activity

Therefore computations for $S_{Logic[i,j]}$ and $F_{Logic[i,j]}$ are formulated to satisfy job logic constraints and are calculated using Eqs. (5.1) and (5.2). The earliest start time $S_{Logic[i,j]}$ that satisfies the job-logic and precedence relationships between activity (i) and all its predecessors is identified by an algorithm that seeks the latest early finish of all activity (i)'s predecessors (algorithm outline is shown in Figure - C.1 in Appendix C). The algorithm is only capable of handling finish-to-start relationships, with or without lag time. For example, if the precedence relationship between two activities is finish-to-start, then the successor activity (i) in each unit (j) can start only after the completion of its predecessor activity ($i - 1$) and the lag time ($lag_{i,i-1}$) between the two activities.

$$S_{Logic[i,j]} \geq \ F_{Logic[i-1,j]} + \ lag_{i,i-1} \tag{5.1}$$

$$F_{logic[i,j]} = \ S_{Logic[i,j]} + d_{i,j} \tag{5.2}$$

These constraints do however not comply with crew availability and continuity constraints and as such computations for $S_{Crew[i,j]}$ and $F_{Crew[i,j]}$ are formulated (Eq. (5.4) and (5.5)) to satisfy these constraints. They shift $S_{Logic[i,j]}$ and $F_{Logic[i,j]}$ to a later date in order to further comply with crew availability constraints, assuming that the first activity has no predecessors and the first repetitive unit (j) can start at time zero as shown in Eq. (5.3) as indicated by the green line on Figure 5.10. They consider (1) the availability of the crew after the completion of work in its previously assigned repetitive unit $F_{Crew[i,j-1]}$; and (2) the specified crew interruption time applied after the completion of the previous unit $j - 1$ ($Integer_{i,j-1}$), as shown in Fig. (5.4).

$$S_{Crew[i,1]} = \ 0 \tag{5.3}$$

$$S_{Crew[i,j]} = \ F_{Crew[i,j-1]} + Integer_{i,j-1} \tag{5.4}$$

$$F_{Crew[i,j]} = \ S_{crew[i,j]} + d_{i,j} \tag{5.5}$$

Once these scheduling constraints have been identified, the time difference $\Delta_{i,j}$ between the earliest start time that satisfies job logic $S_{Logic[i,j]}$ and that which complies with crew availability $S_{Crew[i,j]}$ is calculated as shown in Eq. (5.6). The required delay in $S_{Crew[i,j]}$ and $F_{Crew[i,j]}$ to further satisfy the job logic constraints is represented by the time difference.

$$\Delta_{i,j} = \ S_{Logic[i,j]} - S_{Crew[i,j]} \tag{5.6}$$

The previous step is completed for the same activity (i) in all the repetitive units (J). The maximum time difference ($Shift_i$) is identified with Eq. (5.7) from those calculated in the previous step. It is this shift value which is used to delay $S_{Crew[i,j]}$ and $F_{Crew[i,j]}$ in order to

determine the scheduled start $S_{i,j}$ and finish $F_{i,j}$ times that satisfy all scheduling constraints for activity (i) in each repetitive unit (j) using Eqs. (5.8) and (5.9), as indicated by the orange line in Figure 5.10.

$$Shift_i = \ Max_{J=1}^{J} [\Delta_{i,j}] \tag{5.7}$$

$$S_{i,j} = \ S_{Crew[i,j]} + Shift_i \tag{5.8}$$

$$F_{i,j} = \ S_{i,j} + Shift_i + lag_{i,i-1} \tag{5.9}$$

The total crew interruption days in activity i ($Inter_i$) are calculated with Eq. (5.10) below.

$$Inter_i = \ \sum_{j=1}^{J} Inter_{i,j} \tag{5.10}$$

The total project duration (D) is calculated with Eq. (5.11), by identifying the time difference between the scheduled finish time of the last task in its last repetitive unit ($F_{I,J}$) and the start of the first task in the first unit ($S_{1,1}$).

$$D = \ F_{I,J} - S_{1,1} \tag{5.11}$$

The total number of interruption days (R) for a crew in the project is calculated using Eq. (5.12) below.

$$R = \ \sum_{i=1}^{I} Inter_i \tag{5.12}$$

5.6.3   Integrating schedule and labour transfer time on site

In certain instances the foundation unit is at a distance from site camp, where the transfer time (t_{ij}) of resources is such that it causes delay in the project schedule. In these instances the idle time of resources cause the duration of a specific activity to increase. The increase of an activity duration is dependent on the transfer time (t_{ij}) and the activity duration ($d_{i,j}$) as shown by Eq. (5.13) to (5.17). Therefore in these instances 1 day is added to the duration ($d_{i,j}$) of the activity of that specific foundation unit.

The duration of an activity is increased when the duration of an activity falls within the range of d_{min} and d_{max} , considering the transfer time to the specific antenna foundation.

$$\text{if:} \quad d_{min} \ < \ d_{i,j} \leq \ d_{max} \tag{5.13}$$

$$Fraction \ of \ idle \ time \ per \ day \ (x): \quad \text{With: } x = \ \frac{t_{ij}/60\text{min}}{8 \ hours} \tag{5.14}$$

$$xd_{max} = \ 1 \tag{5.15}$$

$$\text{Number of days when } x \;=\; 1 day\text{:} \qquad d_{max} \;=\; 1/x \qquad\qquad \textbf{(5.16)}$$

$$d_{min} \;=\; d_{max}/2$$

$$then\text{:} \qquad d_{i,j} \;=\; d_{i,j} + 1\, day \qquad\qquad \textbf{(5.17)}$$

In Appendix D, Figure 10.2, the integration is graphically presented in terms of how the activity information is integrated with a demand destination on site. This is a simple application of how the model integrates the schedule with the movement of resources on site. There are, however, many more possibilities which this integration can provide, to measure and manage the effectiveness of the construction operations on site.

5.6.4 Decision variables

There are a number of decision variables considered in the RPS model. The first is required as initial input to the model, as seen in Figure 5.8, and they are: (1) selection of a near-optimal crew formation that can complete an activity of a repetitive unit efficiently; and (2) determining the activity durations based on crew formations. These decision variables are then captured by the RPS mode to generate a project schedule.

Several "what if" analyses can be performed, whereby users change the decision variables and simulate the construction schedule to retrieve the outcome. Users investigate the activity production rates shown in a graphical production curve schedule view, to base decisions on (1) number of crew teams assigned to an activity; and (2) the crew work interruptions between repetitive units; and view the simulation output. Users interactively make changes to the model until a desirable schedule in terms of project duration, resource utilization efficiency and labour cost is obtained.

5.6.5 Objective function

The primary purpose of this module is to manually develop a set of near-optimal construction deployment plans that simultaneously minimizes project duration and maximizes crew work continuity for repetitive construction projects at a feasible labour cost. Therefore there are multiple objects that need to be investigated by the manager when optimizing the schedule, which are: (1) project duration; (2) number of interruptions at project level; (2) resource and labour cost; and (3) slack available in the network.

The calculation of the project duration has been shown in Eq. (5.11). The resource utilization efficiency can be measured by evaluating the total number of interruption days (R) for all crews in the project (see Eq. (5.12)). The total direct cost of labour is calculated by the summation of the multiplication of the number of working days of each crew and their respective daily cost rate (calculated from the daily cost rate of each individual resource in the crew formation).

5.6.6 RPS model validation

It can be seen from the graphical view of the production curve schedule shown in Figure 6.5 that the flexible resource-driven scheduling algorithm, discussed in §5.6.1, executes and performs the scheduling computations correctly. The calculations are shown, for example, containing 8 foundation units, in Appendix C in the Table referenced shown in the right hand column. The use of the model will be shown in CHAPTER 7 during the implementation of the model on a fictitious SKA project.

1.	*updating the activity durations due to the impact of long travel times*	Table - C.1
2.	*computing the resource continuity shift*	Table - C.2
3.	*scheduling the repetitive activities in all repetitive units*	Table - C.3
4.	*showing the result of duration update on production schedule*	Figure - C.3

5.7 Summary

The chapter presented the development of a prototype repetitive project planning system (RPS model) that facilitates the manual optimization of multiple objectives to (1) minimize the project duration; (4) maximize resource utilization; while (3) maintaining a feasible labour cost. The model is designed as an interactive decision tool that provides the expert control over the proceedings, therefore allowing human judgement and experience to be captured.

The model utilizes a flexible algorithm for resource-driven scheduling that automatically generates a project schedule by identifying the scheduled start and finish times for each activity in the repetitive unit. The algorithm allows for (1) the simultaneous assignment of multiple crews; and (2) the assignment of a specific crew work interruption time for a specific activity. The algorithm generates a project schedule that complies with precedence relationships, crew availability and crew work continuity constraints. The scheduling algorithm executes in three phases of which the first two achieve compliance with precedence relationships and crew availability constraints, and the third achieves compliance with the crew work continuity constraint.

The model makes use of unique concepts to both generate an automatic project schedule and integrate the RPS model with the SLP model. The concepts entail (1) creating a repetitive *Process*-object that contains all the repetitive activities and associated crews; and (2) allowing the user to only design this *Process*-object once in terms of activity crew assignment and activity precedence relationship; (3) automatically assigning the *Process*-object to all demand destinations included in the SLP model (i.e. antenna foundations). Therefore in essence the model schedules the activities of a given set of demand destinations automatically while integrating the activity information with the multiple different material supply requirements (i.e. concrete, steel, shutters etc.) of each of the demand destinations on site.

CHAPTER 6

Graphical User Interface (GUI)

A basic user interface that makes it possible for a construction manager with limited programming capabilities to interact with the two models (SLP model and RPS model) is discussed in this chapter. More importantly, the view allows the construction manager to directly access and modify the model. It is through this view that a construction manager can create a custom designed site and apply his practical expertise to interactively optimize the layout by performing various "what if" simulations. The main view application of the GUI is discussed next, followed by an overview of the GUI architecture. A GUI user manual is included in Appendix G, which explains and demonstrates the GUI functionality in more detail.

6.1 Main View Application

The present user interface module is designed to facilitate the following functions: (1) An input phase that facilitates the input of site layout related data; and (2) A graphical view output phase that allows the user to view the site's layout and project schedule graphically; (3) A quantitative measure of the objective functions in each model in order to assess suitability of the site layout and project schedule.

The input phase provides the following functionalities: (1) access and control over assumptions; (2) access and control over facility characteristics already included in the model; (3) ability to create a custom construction facility on site; (4) adding facility operational constraints (i.e. max delivery time); and (5) moving existing temporary facilities or adding more facilities in order to optimize site.

The graphical view provides (1) a site layout with the locations of all temporary facilities and foundations units located on site; and (2) project production curve schedule showing the production rate of each activity. These visual aids help the user to explore possible alternate solutions, and also give guidance to which alternatives to pursue. It also helps a user to remember which arrangements were previously generated, by keeping pictures of the evolving layout and schedule.

The quantitative output phase provides information about each facility (i.e. install cost, delivery points, transport cost, total time of deliveries and average transfer time) and also the total direct and indirect cost. The RPS model provides results regarding the project duration, resource utilization efficiency and the associated direct cost of labour.

6.2   Architecture

The *MainView* is divided into two areas – a main area with a tabbed pane (*LocationView* and *ScheduleView*), for viewing the two models (SLP model and RPS model) and an auxiliary panel (*AuxView*) for viewing more specific information of selected objects in the main area. Figure 6.1 shows the main Class objects of the GUI. There are, however, many panels of type *CurrentPanel* used in the *AuxView*, and can been seen in the project UML diagram shown in Appendix H, Figure - H.1.
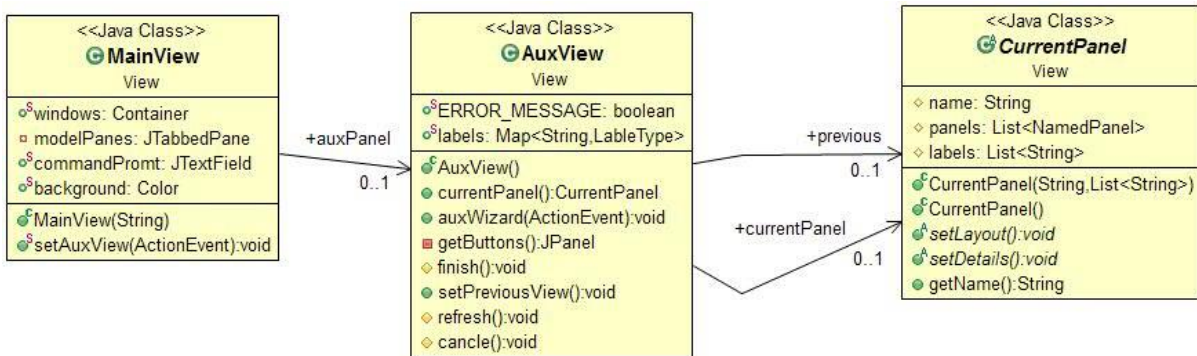

Figure 6.1: UML diagram abstraction of GUI

The following two screenshots of the *MainView* shows some of its functionality. The screenshots are delimited with numbered dashed red boxes for the purpose of explaining the functionality of the various parts of the GUI (refer §6.3).
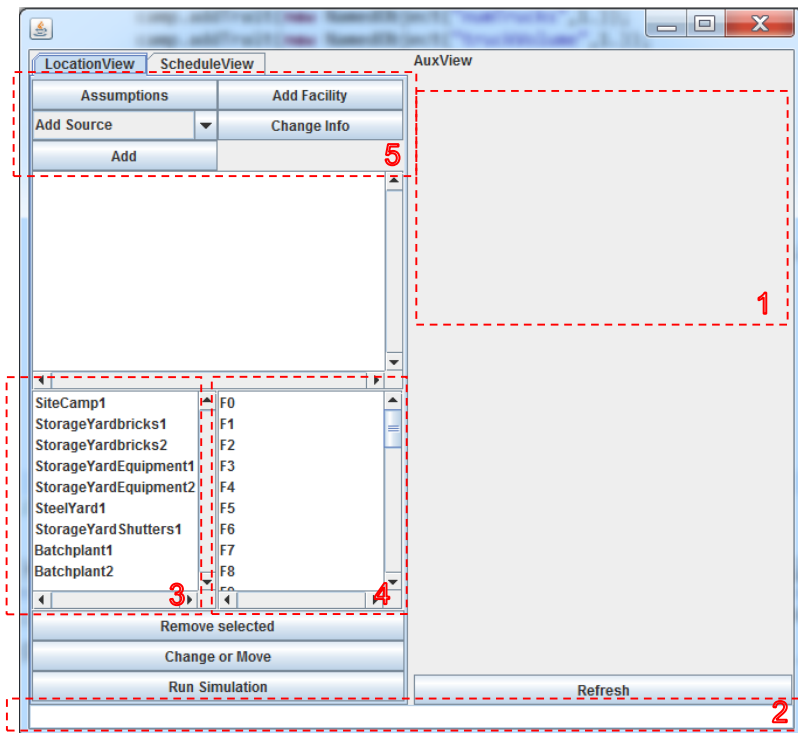

Figure 6.2: Screenshot of the *MainView*

99
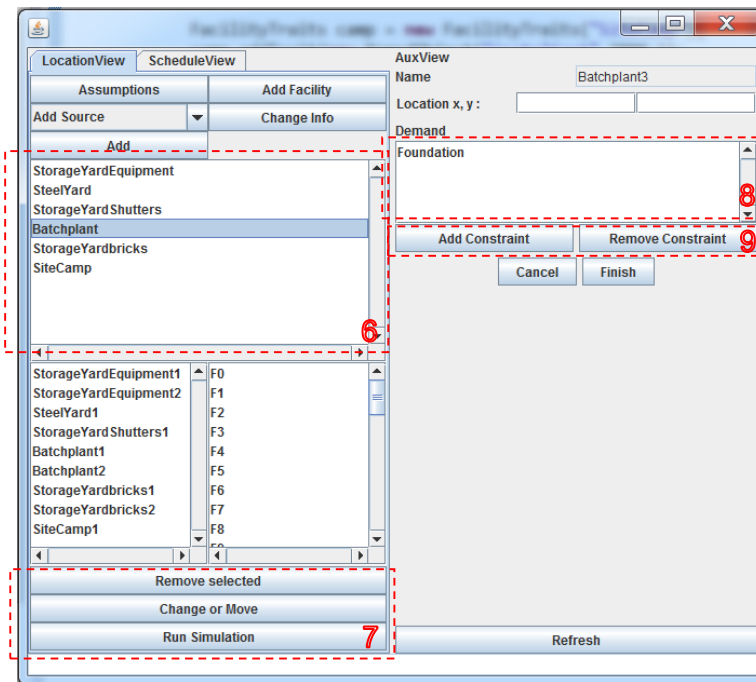
Figure 6.3: Screenshot showing an active *AuxView*

Figure 6.2, shows the "LocationView" being displayed in the main area. It is this view that interacts with the SLP model discussed in CHAPTER 4. The tab at the top of Figure 6.2, called "ScheduleView", is still under development. However, this view will interact with the RPS model. Therefore, at the moment, any changes made to the RPS model are done in the *Main-method* of the RPS model.

In the *AuxView* of Figure 6.3, a facility of type "Batchplant" is displayed with name "Batchplant3". This display is associated with the adding of a facility to the construction site. Note that the name of the facility to be added is "BatchPlant3", since there are already two batch plants located on site, shown in the site data model (see Figure 6.2, box 3).

The AuxView is controlled by an *auxWizard* that displays the appropriate information in the AuxView, depending on what the user has selected in the main view (i.e. in this case the LocationView). The next section provides a brief overview of some of the *MainView* functionalities.

6.3   GUI Functionality

6.3.1   Functionality description

The list below explains the functionalities of the various components, delimited by the dashed red boxes, on the *MainView* area (refer Figure 6.2 and Figure 6.3).

Box 1: This is the *AuxView* that is controlled by the auxWizard to display the appropriate information.

Box 2: This is a command prompt that prompts the user with instructions when a wrong selection has been made.

Box 3: This is the *Source* model, which contains all the *Sources*-objects (facilities) on site.

Box 4: This is the *Destination* model, which contains all the demand destinations (Foundations units) on site.

Box 5: This is a panel containing buttons, providing the functionality to design the construction site.

Box 6: This is a Selection model containing all *Facility* objects, which is the facility types available for selection to be added to the construction site.

Box 7: This is a panel containing buttons, providing the functionality to optimize the construction site.

Box 8: This is a Model that contains the different connections (demands or constraints) between sources and destinations. For example, it can be seen that the *Batchplant3* is connected to a foundation.

It is common to display large amounts of information in a table, but the output console in Eclipse provides a fast and easy way to view the simulation progress and results (Table 6.1 and Table 6.2). Therefore this form of display is used for the SLP model. The RPS model imports the schedule information (i.e. activity start and finish times and crew assignment) into a table. However, both models are supplemented with a graphical display, which makes it possible for the user to visualize the site layout and also the production curve schedule of the project (see Figure 6.4. and Figure 6.5).

Table 6.1: Information output for facility supporting supply demand

```
Batchplant1 Info:
Install Cost: R700000.0
Deliveries: {F0,F1,F2,F3,F4,F5,F6,F7,F8,F9,F10,F11,F12,F13,F14,F15,F16,F17,F18,F19,F20,F
Transport Cost = R 153,835.69
Total Cost = R 853,835.69
TIME = 134.09 days; 3.51 hours avg material handling time per foundation
Avg Truck requierd = 5
```

Table 6.2: Information output for facility supporting visit demand

```
StorageYard6 Info:
Install Cost: R20000.0
Deliveries: {F54,F55,F56,F57,F58,F59,F60,F61,F62,F63}
Transport Cost = R 241,464.09
Total Cost = R 261,464.09
TIME = 5.94 hours (avg time of traval per day for a foundation)
```

6.3.2 Graphical site layout view

The 2D graphical site layout view is generated by a *ShapeDrawer* model. This is done by sending all locations in the SLP model that needs to be drawn on the construction site, to a ShapeDrawer class. The model then draws various shapes to represent the locations of temporary construction facilities and antenna foundations on site. In this case the model used rectangles as shown in Figure 6.4.
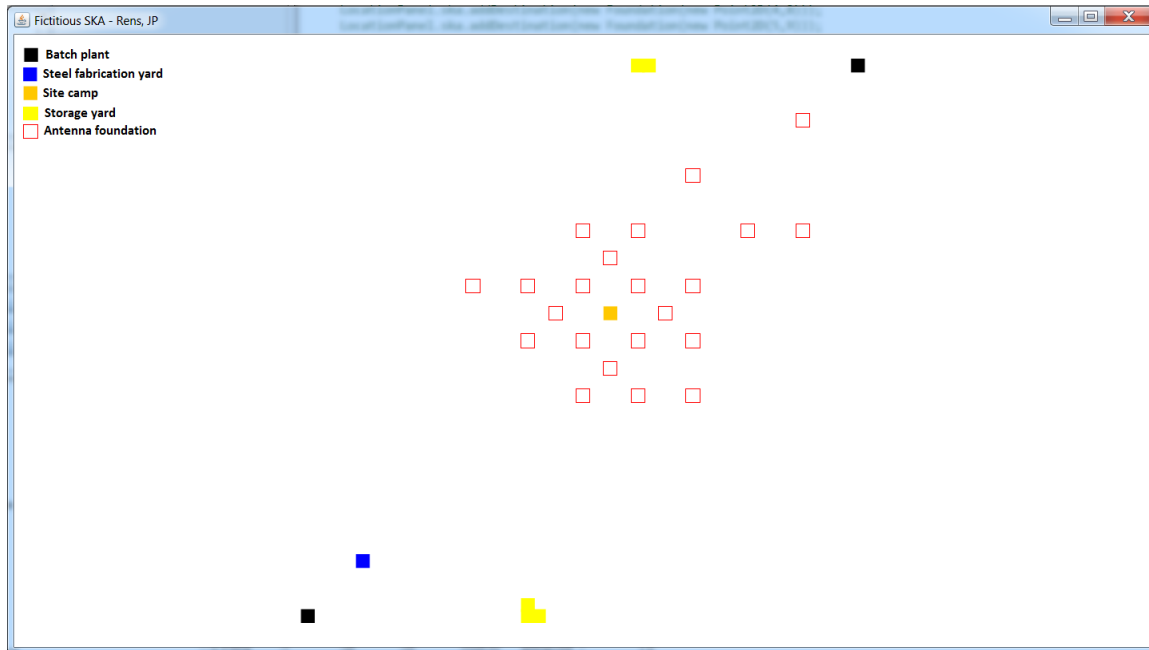
Figure 6.4: 2D graphical site layout view

6.3.3 Graphical production curve schedule view

The graphical production schedule view is generated by a *ScheduleDrawer* model. This is done by sending all activities in the RPS model to a ShapeDrawer class. Each one of the production curves shown in Figure 6.5 are made up of activity line segments for each repetitive unit. Each line segment represents the duration of an activity and is drawn from the scheduled start and finish time. The activity called "Excavate" in Figure 6.5 is an example of when multiple crews are assigned to perform work simultaneously.

The logic involving multiple crew assignment is illustrated in Figure 6.6. It is shown that $Crew_1$ and $Crew_2$ perform work simultaneously. The repetitive units are shown in red. Assigning multiple crews to an activity will reduce the total activity duration in the project, and it is shown here that the RPS model provides this advantage.
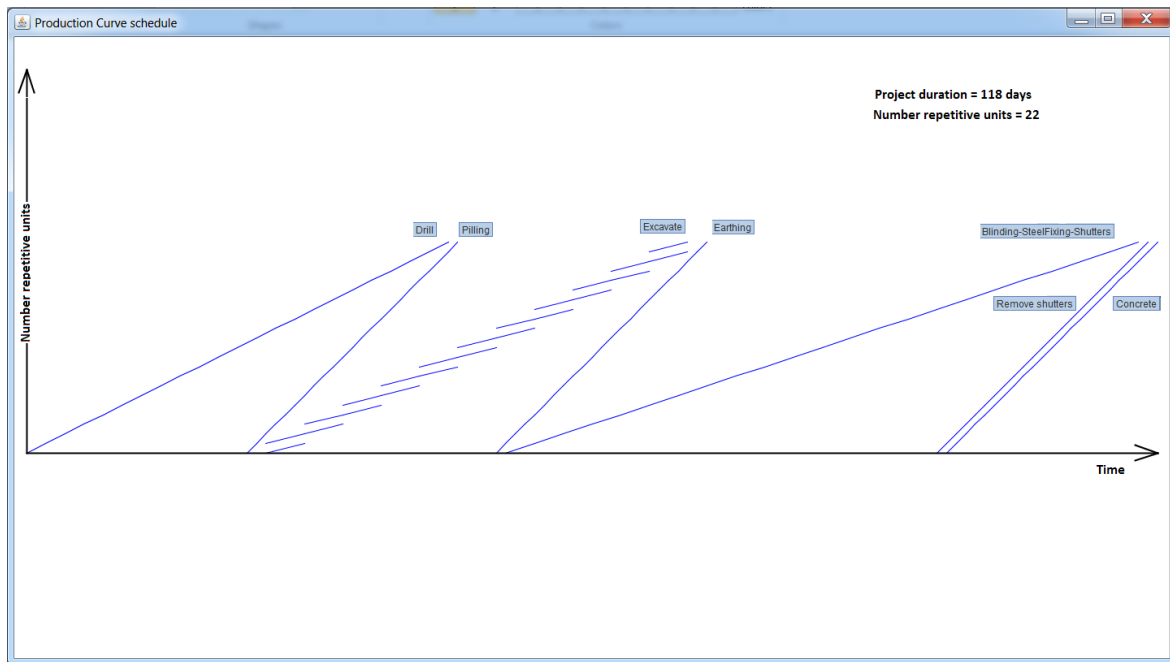
Figure 6.5: Graphical project production schedule view
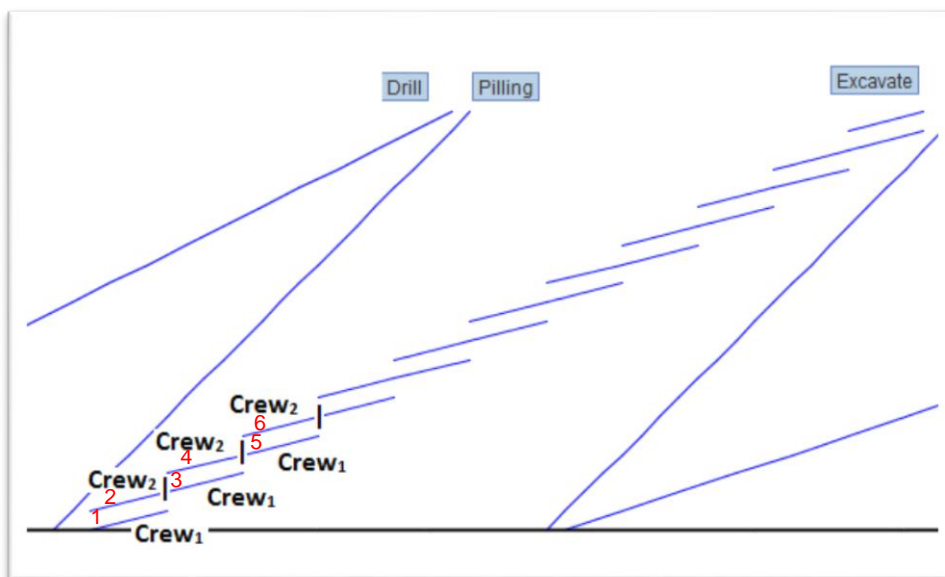
Figure 6.6: Illustrating the multiple crew assignment logic in graphical view

6.4   Summary

This chapter presents (1) an overview of the development of the graphical user interface (GUI) though which a construction manager can interact with the SLP model and RPS model; and (2) an illustration of the graphical output view of the site layout and project production schedule. These visual aids help the user to explore possible alternative solutions, and gives guidance of which alternatives to pursue. It also help a user to remember which arrangements were previously generated, by keeping pictures of the evolving layout and schedule.

CHAPTER 7

Fictitious SKA Project Implementation

The performance of the developed models (site layout planning (SLP) and repetitive project scheduling (RPS) model) will be evaluated in terms of its capabilities to plan (1) the SKA construction site layout; (2) the material supply on site; and (3) the construction project schedule. The models will be evaluated using an example of a fictitious part of the SKA project. This chapter will describe (1) how the fictitious SKA dish configuration was designed to resemble the real SKA; (2) how the RPS model is utilized using a simplified introductory example containing only 20 antenna foundations; and (3) how the model is implemented on the fictitious SKA example containing 191 antenna foundation.

7.1 Introduction

The objective of this chapter is to demonstrate the performance and utilization of the model and therefore a fictitious example layout was used. The model is not applied on the real SKA 1 dish configuration, since the antenna dish locations are sensitive information and was not made available for this research. Also this research was developed independently at Stellenbosch University and not in collaboration with SKAO. Therefore a fictitious example is used here to show how the model can be applied to the real SKA project. All rates and prices used have been assumed, simply to show the application of the model, and they might not be 100% accurate. Nevertheless, this has no influence on the performance evaluation of the model, since an experienced construction manager can choose the true quantities, rates and prices of material, equipment and labour for the real application of the models.

In Bolton et al., (2011) it is said that generic antenna dish layouts for phase 1 and phase 2 of the SKA have been developed. It is stated that the layout of the antennas is important and that "Perfect" layout may seek to provide uniform (logarithmic) coverage in all azimuthal directions. However, layouts designed solely with this in mind tend to be impractical, taking no account of infrastructure cost or of the accessible terrain (Bolton et al., 2011). The SLP model provides the functionality with which the dish layout can be imported and evaluated in terms of infrastructure cost. First the dish layout will be discussed and then how it is imported into the SLP model.

7.1.1 Dish layout

There will be 175 antenna foundations placed in the central 5km radius, which follow a pseudorandom Gaussian distribution (Millenaar et al., 2010). Beyond the core the dishes are located on three spiral arms for SKA 1 and are placed roughly logarithmical in radius

(Dewdney, March 2013). The three SKA 1 spiral arms are a subset of five spiral arms planned for SKA2.

The spirals are similar to log spirals but the arms wind around more tightly closer to the core, in order to effectively smooth the transition from the core into the arms. The spiral arms follow Eq. (7.1), where r is the radius from the centre, θ is the polar angle and the constants are a=2.5km, b=1.5 and Φ=4.0 (Bolton et al., 2011).

$$r = \quad a \cdot exp\left(\frac{b\theta^{\ 3}}{(\theta + \Phi)^2}\right) \tag{7.1}$$

7.1.2 Fictitious SKA antenna layout design

In order to create the fictitious SKA project that resembles the true configuration, the spiral arms and dense inner core were designed as follows: (1) Eq. (7.1) was simulated three times (i.e. once for each spiral) using different constants to populate the spirals, with 60 locations for antenna foundation units in the SLP model (i.e. *Destinations*). The dense inner 5km region was populated by generating 131 locations for antenna foundation units inside a central 5km diameter circle. Figure - E.1 and Figure - E.2 , in Appendix E show the spirals and inner core of the fictitious project in the graphical SLP model view. This graphical view can be compared with the true spirals (Figure - E.3) and the dense inner core (Figure - E.4) of SKA 2.

It becomes clear that the model developed in this study can be used to evaluate the feasibility of various dish configurations in terms of infrastructure cost and construction duration. Also the model provides a suitable framework for further development to increase the functionality of such a management system, especially during the construction deployment planning of Phase 2, shown in Appendix E.

7.2 Introductory example

This section uses a simple example, containing only 20 antenna foundations, to show how the RPS can be used to reduce the schedule. A smaller number of antenna foundations is used to clearly show how the production schedule in the graphical view changes while the construction duration is reduced.

RPS model example

Table 7.1 lists the results from the interactive optimization procedure followed in order to reduce the project schedule. In order to do so four simulations were executed, as shown in Table 7.1. The functions performed in each of the schedules are described in the list below. Each schedule option has a graphical view of the production schedule to show the changes. The graphical view of each schedule is shown in Appendix E.

Schedule 1: It entailed generating the project schedule for the first time without any resource interruptions. This resulted in a total project duration of 146 days.

Schedule 2: It entailed assigning 3 crews to "activity 3" and 2 crews to "activity 5". This resulted in project reduction of 77 days.

Schedule 3: It entailed assigning a crew interruption of 1 day to "Crew 2". It can be seen that the project is reduced by 7 days, but the labour cost has increased.

Schedule 4: It entailed removing the 1 day interruption of "Crew 2" and assigning 2 crews to "Activity 1", thus reducing the total project duration by 96 days from schedule 1.

Table 7.1: Introductory scheduling example

Schedule	Project duration	Interruptions	Labour cost	Reference
1	146	0	R471 930.88	Figure - E.5
2	69	0	R471 930.88	Figure - E.6
3	62	20	R502 063.36	Figure - E.7
4	50	0	R471 930.88	Figure - E.8

This example has briefly shown how the project schedule of SKA can be minimized while maximizing resource utilization. The same procedure and configuration will be applied in the fictitious example, discussed next.

7.3 Fictitious SKA implementation

This section presents the implementation of both models, SLP model and RPS model, on the chosen fictitious SKA project in order to (1) minimize site layout cost[1] (2) reduce travel time on site (3) reduce the project duration; and (4) maximize resource utilization. Note that the result shown here are not the best solutions but an optimum or a most favourable solution that can be selected out of a set of pursued alternatives. However, taking into account the various decision variables across site layout planning, material procurement and resource scheduling, there are an infinite number of possibilities.

7.3.1 Assumptions

All parameters and values used in the models were assumed after consultation with Le Roux (28 February 2015), the full time construction manager on the precursor MeerKAT project (see Appendix A). The accuracy of these values is not important for the purpose of this exercise, since the objective is to show how the model can be utilized. When a construction manager uses the model he can choose the correct values. However, in order to be realistic and to maintain originality in the fictitious project, these values can be considered reasonable.

---

[1] Site establishment cost and transportation cost

Assumptions used primarily in the SLP model are shown in Table - F.1, Table - F.2 and Table - F.3.

7.3.2 Site layout planning (SLP) simulation results

Site Layout optimization strategy

The first step to planning a construction layout is to identify the facilities needed to support construction operations of the 190 antenna foundations. In this example four facilities have been chosen to be located on site, as listed in Table 7.2. However, a construction manager can add many more to the site. In order to reduce travel cost and time on site, three layout and two material supply alternatives were pursued. For the purpose of this exercise it is investigated which is more feasible: a centralized construction area containing 1 of each construction facility, or a decentralized construction area with multiple construction facilities of the same type.

Table 7.2 lists the results from the interactive optimization procedure followed in order to reduce the layout cost and travel time. From layout 1- 2 the number of temporary construction facilities were increased as shown in the column titled "Facilities used". From layout 2-3 the number of material handling equipment (i.e. trucks) is increased, as shown in the column titled "Trucks used". The functions performed in each of the layouts are summarised in the list below Table 7.2.

Table 7.2: SLP results

Layout	Facility	Facilities used	Establishment cost (R 10^3)	Travel cost (R 10^3)	Avg. transfer time		Delivery time (days)	Total cost (R 10^3)	Trucks used
1	Batch plant	1	R 700	R 153.84	3.51	hours/f*	135	R 854	4
	Steel yard	1	R 2 250	R 112	4.53	hours/f	109	R 2 362	1
	Storage yard	1	R 20	R 1 759	3.5	hours/f/day		R 1 779	1
	Site camp	1	R 200	R 1 300	2.83	hours/f/day		R 1 500	1
			R3 170	**R3 325**				**R6 495**	
2	Batch plant	2	R 1 400	R 124	3.22	hours/f	122	R 1 524	4
	Steel yard	1	R 2 250	R 112	4.53	hours/f	109	R 2 362	1
	Storage yard	6	R 120	R 1 064	2.91	hours/f/day		R 1 184	1
	Site camp	4	R 800	R 943	2.42	hours/f/day		R 1 743	1
			R4 570	**R2 243**				**R6 813**	
3	Batch plant	1	R 700	R 153.84	3.21	hours/f	123	R 854	5
	Steel yard	1	R 2 250	R 112	2.77	hours/f	66	R 2 362	2
	Storage yard	6	R 120	R 1 064	1.45	hours/f/day		R 1 184	2
	Site camp	4	R 800	R 943	2.42	hours/f/day		R 1 743	1
			R3 870	**R2 273**				**R6 143**	

f = antenna foundation unit

Layout 1: Entailed locating one of each of the 4 temporary construction facilities shown in Table 7.2.

Layout 2: Entailed locating an additional 5 storage yards, 3 site camps and an extra batch plant on site. Layout 2 consists of three site camps in the dense core and one in each of the three spirals. Three additional site camps were also located in the spirals next to each storage yard and two batch plants on either side of the core. The qualitative advantages of this layout have been discussed in §2.2.1.

Layout 3: Entailed removing one batch plant and increasing the units of material handling equipment operating from the batch plant, storage yard and site camp.

Additional results

Not shown in Table 7.2 is the set of foundations that belong to each of the construction facilities as shown in Table 6.1 and Table 6.2. This information can be used to effectively plan the onsite delivery of material. Thus in layout 3, containing 6 storage yards, each storage yard will have its own particular set of antenna foundations. This functionality makes it clear which foundations belong to which of the construction areas (i.e. construction facilities) in the case where a decentralized construction area (such as layout 3) is selected.

The truck requirement for the concrete delivery to each individual antenna foundation unit was calculated. Although the specific number of trucks required by each individual foundation unit is known (see §4.7.4), this is not a practical answer to the situation of implementing on site. Therefore an average number of trucks were calculated for the duration of concrete delivery on site (see Table 7.2, column titled "Delivery time"). It was found that an average of 5 trucks is required and in Layout 3 this was accordingly changed from 4 trucks to 5 trucks (see Table 7.2).

Concluding site layout results

The findings in Table 7.2 are summarised with (1) Figure 7.1: Travel cost on site; (2) Figure 7.2: Transfer time on site; and (3) Figure 7.3: Total layout cost.

The results indicate that the model is capable of simulating the flow of resources on site and measuring the travel distances from temporary construction facilities to antenna foundation units. This information can then be used to evaluate and optimize alternative site layouts. An interactive procedure was used to optimize the site layout by performing three "what-if" simulations.
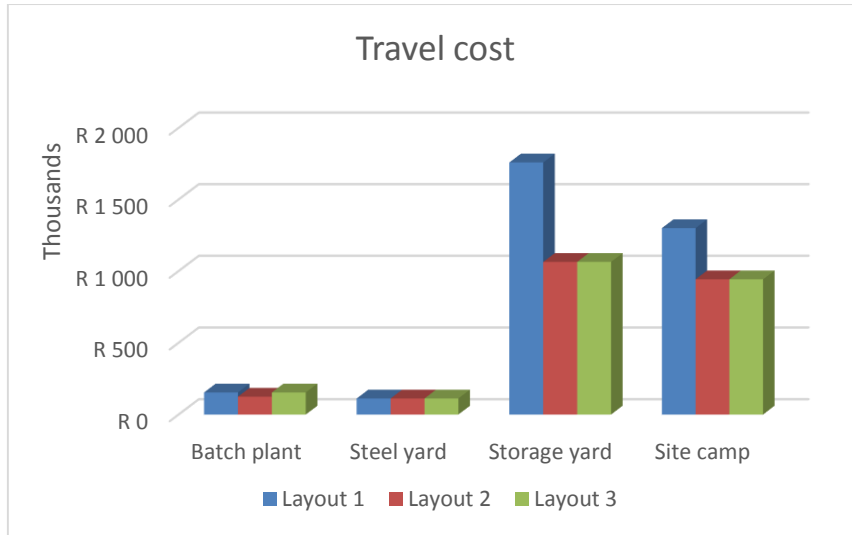
Figure 7.1: Travel cost on site
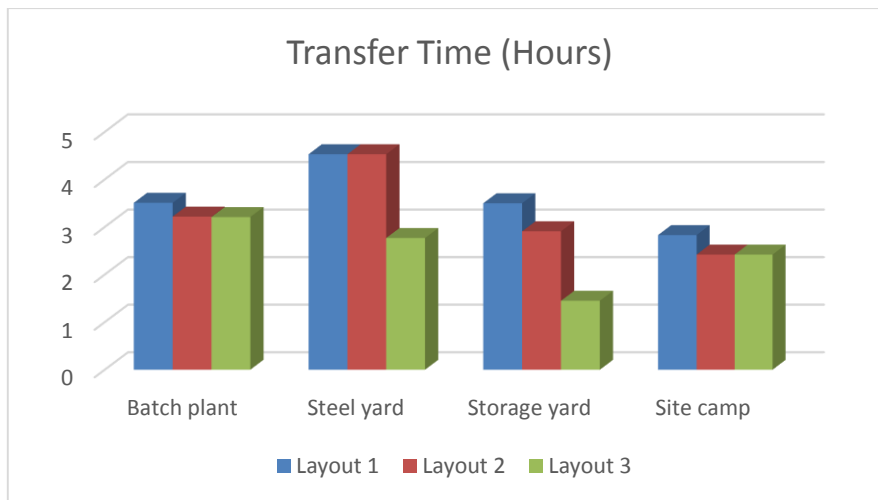
Figure 7.2: Transfer time on site
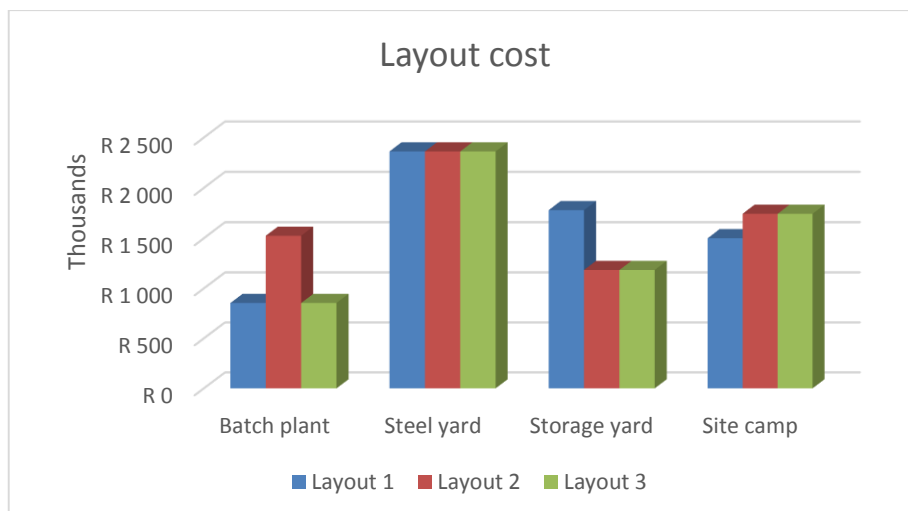
Figure 7.3: Total layout cost

With regards to the fictitious SKA example it is found that the establishment cost of temporary construction facilities is expensive with regards to the travel cost from the respective facilities. However, when multiple storage yards and site camps are used, the transfer time on site is reduced. This can increase the productivity of the construction operations on site and enhance the efficiency of construction. This benefit can be achieved at a lower total layout cost (i.e. establishment and travel cost) as shown by layout 3 in Table 7.2. The logic applied, using a decentralized construction area with multiple storage areas and site camps, will provide a greater benefit in SKA 2 when the number of antenna foundations are increased. Therefore the SLP model must be utilized by also taking into consideration the qualitative advantages and disadvantages of the respective layout alternatives, as discussed in §2.1.1.

7.3.3   Repetitive project scheduling (RPS) results

The construction activities required at an antenna foundation unit, their respective durations and their required labour and equipment resources have been discussed in Table 2.1. The assumptions of the hourly rates are shown in Table - F.3. The RPS model was implemented using the same simulation procedure as discussed in §7.2. However, three practical alterations were made, as listed below:

1) An extra activity has been added that is not performed at a foundation unit, but at the steel fabrication yard. This activity is listed first in Table 2.1 and has also been shown in Table 7.5.

2) In order to deliver a practical schedule a 3 day lag value was assigned to the "concreting" activity performed by crew 3 and crew 7, as discussed in Table 2.1.The duration marked in red in Table 7.3 shows the result without taking the lag values into consideration. Thus 6 days are added to the project duration.

3) The increase in activity duration due to large resource travel times were taken into consideration as discussed in §5.6.3. Table 7.4 presents how a site layout can reduce the project duration. The impact of long travel distances to specific activities is shown in red for schedule 4 in Table 7.5.

It can be seen from Table 7.3 that the project duration was successfully minimized from 1363 days to 372 days. Note that the project cost does not increase when more resources are assigned, since the cost of crashing an activity was not taken into consideration. This is discussed in §5.3.2. Also note that labour cost increases when crew work interruptions are assigned. Table 7.5 shows the change in resource assignment in schedule 1 (*S1*) and schedule 4 (*S4*).

Table 7.3: RPS model results at project level

Schedule	Project duration (days)	Interruptions (days)	Labour cost
1	1357*1363	0	R 21 770 618
2	562	0	R 21 770 618
3	498	191	R 24 055 634
4	372	0	R 21 824 321

The project duration without taking activity lag into consideration.

Table 7.4 shows how the increase in project duration due to long travel distances to antenna foundations units can be minimized by selecting a suitable site layout. Results show that when a combination of schedule 1 *(S1)* and layout 1 is used the effect of resource travel time increases the project duration with 30 days (red in Table 7.4). This is illustrated by comparing *S1* with and without updating the activity tasks ($d_{i,j}$), as discussed in §5.6.3. However, the impact of 30 days can be reduced to 12 days by selecting site layout 3, as shown in Table 7.4. This will also lead to cost savings on direct labour as shown in Table 7.4. Still the preferred option is a combination of schedule 4 (*S4* in Table 7.5) and layout 3 (in Table 7.2).

Table 7.4: Effect of resource travel time on project schedule

	No Update ($d_{i,j}$)	Update ($d_{i,j}$)		Savings on direct labour
		layout 1	layout 3	
Schedule 1 *(S1)*	1351	1381 (30)*	1363 (12)*	R 161 009
Schedule 4 *(S4)*	372	386 (14)*	380 (8)*	R 101 697

Increase in project duration (days) due to the impact of resource travel time on site.

Table 7.5: RPS model at activity level

Crew	Activity	Crews used		Duration (days)		Direct labour and equipment cost
		S1	*S 4*	*S1*	*S4*	
1	8 Steel reinforcement cages	1	2	382	192 +2*	R 915 578
2	Drill foundation piles	1	2	382	192+2*	R 9 341 581
3	Insert steel cages in piles + cast concrete	1	1	194	194	R 2 298 042
4	Excavate platform	1	3	764	256+3*	R 5 684 771
5	Earthing	1	1	191	191	R 163 496
6	Blinding layer	1	2	573	288+3*	R 1 545 725
	Steel Reinforcement					
	Install and remove Shutters					
7	Concrete	1	1	191	194	R 335 396
8	Remove shutters & Back fill1	1	1	191	191	R 1 413 094
	Total:	8	13	1363	372+8**	R 21 824 321 R 190 557***

* *Increase in activity duration (days) due to the impact of resource travel time on site.*
** *Increase in project duration (days) due to the impact of resource travel time on site.*
*** *Increase in project direct labour and equipment cost due to the impact of resource travel time on site.*

Concluding the RPS results

The RPS model can be utilized by a construction manager to plan and design a construction schedule for the SKA project. The project duration and resource utilization can be manually optimized by providing the construction manager with control over the proceedings of assigning labour crews and crew work interruptions. The RPS model is capable of measuring the impact of long travel times of labour resources on the construction activity, total project duration and direct labour cost, thus in this way integrating site layout planning and project scheduling. This integration makes it possible to evaluate various site layouts in terms of how they perform with regards to the project duration. The model uses minimum user input to instantaneously program the project schedule and therefore this makes the model an easy tool to use and evaluate various alternatives.

7.4   Summary

This chapter presented an evaluation of the performance of the models developed, by implementing the SLP model and the RPS model on a fictitious SKA project. In order for the findings to be realistic and practical the fictitious project was chosen to resemble the true dish layout of the SKA 1. Estimations of quantities and rates were also obtained through consultation with the construction manager on the MeerKAT project. It was shown that the antenna dish configuration can be simulated and its locations be easily imported in the SLP model. This makes it possible to easily evaluate the constructability of various dish configurations.

It was shown that the SLP model is capable of simulating the flow of resources on site and in measuring the travel distances from temporary construction facilities to antenna foundation units. This quantitative measure makes it possible for a manager to evaluate various site layout configurations and to optimize the layout by adding and moving temporary construction facilities in order to reduce the travel cost and time on site. Travel time can further be minimized by using more material handling equipment at a temporary construction facility. The RPS model was capable of reducing the fictitious project duration from 1363 days to 372 days, while maintaining resource continuity. The integration of the SLP model and RPS model allows for the impact of resource travel times on site to be shown in the project schedule. Results show that the selection of an inefficient site layout that causes long travel times can lead to an increase in the project duration. This type of information is important to the successful planning of the construction deployment on SKA. The model uses minimum user input to instantaneously program the project, which ensures resource continuity. Therefore this makes the model an easy tool to use to evaluate various alternatives and to measure the site layout in terms of its impact on the project schedule. It was also shown how the model complies with practical constraints such as activity lag duration and how it is capable of scheduling multiple labour crews simultaneously.

The findings on the fictitious SKA 1 show that a decentralized construction site entailing multiple site camps and storage yards reduces the resource and material handling time on site. This could be achieved at a lower total layout cost with respect to a centralized construction camp from where all activities are deployed. Also, such a layout results in a shorter project duration compared to the centralized construction camp. It was found that the fictitious project could be completed within an effective time of roughly 1 year if 13 crews are deployed, with some performing work simultaneous on activities with a longer unit production rate.

CHAPTER 8

CONCLUSION

8.1 Thesis Summary

This research study focused on the development of a decision support model that can be used by a construction manager as a planning tool for the construction deployment of antenna infrastructure on the SKA project. Various strategies and alternative approaches were investigated to overcome the construction challenges posed by SKA, and to include these strategies in an integrated model. The investigation entailed a review on various models utilized by different industries to overcome similar challenges. Many of these models execute like black box systems and utilize intelligent heuristic optimization techniques to automatically solve multiple objectives. Others use an interactive approach which provides the user with control over the proceedings. The focus of literature review was on (1) facility location models, specifically the models developed to address the site layout planning problem; and (2) scheduling methods that are capable of scheduling projects with repetitive activities.

The model framework developed in this study uses a unique concept to simulate the flow of dynamic entities on site and is structured to integrate site layout planning, material handling and repetitive project scheduling in one system. The approach followed allows for human judgement and the experience of an expert to be captured during the site layout planning and scheduling of the repetitive construction activities. Thus the prototype decision support software is designed as an interactive management system that provides a graphical user interface and 2D visual communication.

The SLP model facilitates the manual optimization of site layout planning and on-site material supply. The model utilizes a simulation-based framework which makes it possible for construction managers to perform a series of "what if" analyses to optimize the site layout. The SLP model can be used as a decision tool to aid construction managers in minimizing the site layout cost[1] and total site transportation time. The model makes use of a unique concept to determine the dynamic flow of resources between temporary construction facilities and demand destinations on site. The concepts entail (1) creating a generic temporary construction facility; (2) creating a demand destination on site with multiple different demand requirements (i.e. concrete, steel, shutters etc.); (3) connecting material sources and demand destinations in a continuous 2D space; (4) simulating the handling of material from sources to demand

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[1] This cost element includes travel cost and site establishment cost

destinations, considering material handling equipment (i.e. trucks). Therefore the SLP framework is formulated in a way that makes it possible for the user to design the site layout manually by creating a customized temporary facility (batch plant, storage yard etc.) and to design the flow of resources on site.

The RPS model facilitates the manual optimization of multiple objectives to (1) minimize the project duration; (2) and maximize resource utilization; while (3) maintaining a feasible labour cost. The model is designed as an interactive decision tool that provides the user control over the proceedings, therefore allowing human judgement and experience to be captured. The model utilizes a flexible algorithm for resource-driven scheduling that automatically generates a project schedule by identifying the scheduled start and finish times for each activity in the repetitive unit. The algorithm allows for (1) the assignment of multiple crews to perform work simultaneously; and (2) the assignment of a specific crew work interruption time for a specific activity. The algorithm instantaneously generates a project schedule that complies with scheduling constraints, such as (1) precedence relationship amongst activities; (2) crew availability; and (3) crew work continuity. The RPS model framework makes use of a unique concept to both automatically generate a project schedule and integrate the RPS model with the SLP model. This framework requires minimum user input and enables a user to program an entire project schedule instantaneously, which makes it the ideal tool to evaluate various alternatives.

In order to allow the user to interact with the model a graphical user interface (GUI) was designed to provide the necessary functionality to design a construction site layout and constraints. Both models deliver a graphical output that can be used as visual aids to help the user explore possible alternate solutions, and also provide guidance to which alternatives to pursue. It also helps a user to remember which arrangements were previously generated, by keeping pictures of the evolving layout and schedule. This functionality enhances the practicality the models provide.

The model's performance was evaluated by implementing it on a fictitious SKA project designed to resemble the dish layout of the true SKA phase 1. The model evaluation showed that it can be utilized to (1) minimize transportation time and cost while considering resource movement and material handling on site; (2) minimize project duration; (3) maximize resource utilization; and (4) integrate material supply and resource travel idle time with project schedule in order to determine the effect it has the construction duration.

With regards to the findings on the fictions SKA project, it was found that a decentralized construction camp may result in more efficient operations due to a reduced transfer time of resources and material on site with respect to a centralized construction camp from where all

activities are deployed. It was also shown that a centralized construction camp can cause long travel times of resources which result in an increase in the project duration. The impact of transfer time of resources can however be reduced by using a decentralized construction area. The exact number of antenna foundations included in each construction area is determined by the model. These results are, however, very dependent on the assumed establishment and transportation cost, items which can easily be defined by an experience manager.

8.2   Recommendations for future developments

The models developed in this study are suitable frameworks on top of which an optimization algorithm can be executed to address some of the complex problem dynamics. Examples of such implementation on the SLP framework is (1) an algorithm that automatically searches for the best layout in order to reduce the number of user interventions and to guide the user in the proceedings of finding near-optimal solutions; and (2) an algorithm that updates the location of positional temporary facilities in order to consider the dynamic relocation of facilities by producing a site layout over time (dynamic layouts). Such developments have been briefly discussed in terms of model formulation, decision variables and geometrical constraints. Room for optimization in the RPS framework is to develop an algorithm that delivers a pre-specific target completion date by determining the optimum number of crews assigned to each task, considering the possibility of crew work interruption and maximizing resource utilization.

During the construction of SKA 2, space management in the core will be challenging since the construction of 900 antenna foundations within a 5km radius will cause severe congestion in this area. The management of material deliveries in such a congested area can lead to a major loss in productivity and efficiency. Therefore strategies such as "space scheduling" can be investigated to overcome this challenge.

In conclusion, the integration of site layout planning, material supply and scheduling provides a framework that opens up a variety of possible improvements across these areas.

CHAPTER 9

References

Blum, C. & Roli, A. 2003. Metaheuristics in Combinatorial Optimization: Overview and Conceptual Comparison. *ACM Computing Surveys (CSUR),* 35(3). :268-308.

Bolton, R., Millenaar, R. P. & Harris, G. D. 2015. *"SKA CONFIGURATIONS DESIGN".* [Online]. Available: http://www.skatelescope.org/publications/

Brotcorne, L., Laporte, G. & Semet, F. 2003. Ambulance Location and Relocation Models. *European Journal of Operational Research,* 147(3). :451-463.

Calis, G. and Yuksel, O. 2010. A Comparative Study for Layout Planning of Temporary Construction Facilities: Optimization by using Ant Colony Algorithms. Paper presented at International Conference on Computing in Civil and Building Engineering.

Chau, K. 2004. A Two-Stage Dynamic Model on Allocation of Construction Facilities with Genetic Algorithm. *Automation in Construction,* 13(4). :481-490.

Cheng, M. & O'Connor, J. 1996. ArcSite: Enhanced GIS for Construction Site Layout. *Journal of Construction Engineering and Management,* 122(4). :329-336.

Cho, K., Hong, T. & Hyun, C.T. 2013. Space Zoning Concept-Based Scheduling Model for Repetitive Construction Process. *Journal of Civil Engineering and Management,* 19(3). :409-421.

Coello, C.A.C., Van Veldhuizen, D.A. & Lamont, G.B. 2002. *Evolutionary algorithms for solving multi-objective problems.* Springer

Colmant, A. 2015. *Decision support for resource assignment to counter maritime threats in the economic exclusion zone. Unpublished thesis.* Stellenbosch: Stellenbosch University.Masters of Science

Devi, A.C. and Ananthanarayanan, K. 2007. A Model for Automated Generation of Resource-Driven Construction Schedule for Housing Industry. Paper presented at 24th International Symposium on Automation & Robotics in Construction ISARC 2007), Construction Automation Group, I.I.T. Madras.

Dewdney, P. 2015. *SKA memo 130, "SKA phase 1: Preliminary system description",* [Online]. Available: www.skatelescope.org/pages/page_memos.htm

Dewdney, P. E. 2015. *"SKA1 SYSTEM BASELINE DESIGN".* [Online]. Available: http://www.skatelescope.org/publications/

Easa, S.M. & Hossain, K.M.A. 2008. New Mathematical Optimization Model for Construction Site Layout. *Journal of Construction Engineering and Management,* 134(8). :653-662.

Elbeltagi, E., Hegazy, T. & Grierson, D. 2005. Comparison among Five Evolutionary-Based Optimization Algorithms. *Advanced engineering informatics,* 19(1). :43-53.

Elbeltagi, E., Hegazy, T., Hosny, A.H. & Eldosouky, A. 2001. Schedule-Dependent Evolution of Site Layout Planning. *Construction Management & Economics,* 19(7). :689-697.

El-Rayes, K. & Moselhi, O. 2001. Optimizing Resource Utilization for Repetitive Construction Projects. *Journal of Construction Engineering and Management,* 127(1). :18-27.

El-Rayes, K. & Moselhi, O. 1998. Resource-Driven Scheduling of Repetitive Activities. *Construction management & economics,* 16(4). :433-446.

El-Rayes, K. & Said, H. 2009. Dynamic Site Layout Planning using Approximate Dynamic Programming. *Journal of Computing in Civil Engineering,* 23(2). :119-127.

Esfahan, N.R. & Razavi, S. 2015. Scheduling Optimization of Linear Projects Considering Spatio-Temporal Constraints.

Halpin, D.W. 2010. *Construction management.* John Wiley & Sons

Halpin, D.W. 1992. *Planning and analysis of construction operations.* John Wiley & Sons

Harmelink, D.J. & Rowings, J.E. 1998. Linear Scheduling Model: Development of Controlling Activity Path. *Journal of Construction Engineering and Management,*

Harris, F. & Mc Caffer, R. 1980. *Worked examplesin construction management.* Great Britain: Granada Publishing

Harris, R.B. & Ioannou, P.G. 1998. Scheduling Projects with Repeating Activities. *Journal of Construction Engineering and Management,* 124(4). :269-278.

Hassanein, A. & Moselhi, O. 2005. Accelerating Linear Projects. *Construction Management and Economics,* 23(4). :377-385.

Hyari, K. & El-Rayes, K. 2006. Optimal Planning and Scheduling for Repetitive Construction Projects. *Journal of Management in Engineering,* 22(1). :11-19.

Irizarry, J., Karan, E.P. & Jalaei, F. 2013. Integrating BIM and GIS to Improve the Visual Monitoring of Construction Supply Chain Management. *Automation in Construction,* 31:241-254.

Jang, H., Lee, S. & Choi, S. 2007. Optimization of Floor-Level Construction Material Layout using Genetic Algorithms. *Automation in Construction,* 16(4). :531-545.

Jun, D.H. 2010. *Multi-objective optimization for resource driven scheduling in construction projects. Unpublished thesis.* University of Illinois at Urbana-Champaigne.Ph.D

Kandil, A., El-Rayes, K. & El-Anwar, O. 2009a. Optimization Research: Enhancing the Robustness of Large-Scale Multiobjective Optimization in Construction. *Journal of Construction Engineering and Management,* 136(1). :17-25.

Kandil, A., El-Rayes, K. & El-Anwar, O. 2009b. Optimization Research: Enhancing the Robustness of Large-Scale Multiobjective Optimization in Construction. *Journal of Construction Engineering and Management,* 136(1). :17-25.

Konak, A., Coit, D.W. & Smith, A.E. 2006. Multi-Objective Optimization using Genetic Algorithms: A Tutorial. *Reliability Engineering & System Safety,* 91(9). :992-1007.

Lafarge. 2015. *Calculating truck requierments.* [Online]. Available: http://www.lafarge-na.com/wps/portal/na/en/3_A_11_1-Calculating_Truck_Requirements

Lekalake, T. 2015. *"PRELIMINARY DESIGN REPORT (PDR) FOR THE ANTENNA FOUNDATIONS SUB ELEMENT".* [Online]. Available: http://www.skatelescope.org/publications/

Lekalake, T. 2015. *"SKA1_MID INFRASTRUCTURE AND POWER CONSTRUCTION DEPLOYMENT STRATEGY".* [Online]. Available: http://www.skatelescope.org/publications/

Lekalake, T. "SKA1 INFRASTRUCTURE AND POWER DEPLOYMENT STUDY SCPOPE OF WORK"Stellenbosch University

Liao, T.W., Egbelu, P., Sarker, B. & Leu, S. 2011. Metaheuristics for Project and Construction management–A State-of-the-Art Review. *Automation in Construction,* 20(5). :491-505.

Ma, Z., Shen, Q. & Zhang, J. 2005. Application of 4D for Dynamic Site Layout and Management of Construction Projects. *Automation in Construction,* 14(3). :369-381.

Maghrebi, M., Travis Waller, S. & Sammut, C. 2014. Assessing the Accuracy of Expert-Based Decisions in Dispatching Ready Mixed Concrete. *Journal of Construction Engineering and Management,* 140(6).

Maghrebi, M., Waller, T.S. and Sammut, C. 2013. Scheduling Concrete Delivery Problems by a Robust Meta Heuristic Method. Paper presented at Modelling Symposium (EMS), 2013 European. IEEE, 2013.

Mahdi, I.M. 2004. A New LSM Approach for Planning Repetitive Housing Projects. *International Journal of Project Management,* 22(4). :339-346.

Mallasi, Z. 2006. Dynamic Quantification and Analysis of the Construction Workspace Congestion Utilising 4D Visualisation. *Automation in Construction,* 15(5). :640-655.

Millenaar, R. P. & Dewdney, P. 2015. *"SKA CONFIGURATIONS DESIGN: STATUS JANUARY 2010".* [Online]. Available: http://www.skatelescope.org/publications/

Moselhi, O. & Hassanein, A. 2003. Optimized Scheduling of Linear Projects. *Journal of Construction Engineering and Management,* 129(6). :664-673.

Said, H.M. 2010. *Optimizing site layout and material logistics planning during the construction of critical infrastructure projects. Unpublished thesis.* University of Illionios.Ph.D

Said, H. & El-Rayes, K. 2014. Automated Multi-Objective Construction Logistics Optimization System. *Automation in Construction,* 43:110-122.

Selinger, S. 1980. Construction Planning for Linear Projects. *Journal of the Construction Division,* 106(ASCE 15504).

SKA South Africa. 2015. MᴇᴇʀKAT. [Online]. Available: http://www.ska.ac.za/meerkat/ [15/02/2015]

SKA South Africa. 2015. *Square kilometre array.* [Online]. Available: http://www.ska.ac.za

Srisuwanrat, C. 2009. *The sequence step algorithm a simulation-based sceduling algorithm for repetitive projects with probability activity durations. Unpublished thesis.* The University of Michigan.Ph.D

Stevenson, T. & Spyromilio, J. 2013. SKA System Engineering Management Plan.

Suman, B. & Kumar, P. 2006. A Survey of Simulated Annealing as a Tool for Single and Multiobjective Optimization. *Journal of the operational research society,* 57(10). :1143-1160.

Thomas, H.R., Riley, D.R. & Messner, J.I. 2005. Fundamental Principles of Site Material Management. *Journal of Construction Engineering and Management,*

Tommelein, I., Levitt, R. & Hayes-Roth, B. 1992a. SightPlan Model for Site Layout. *Journal of Construction Engineering and Management,* 118(4). :749-766.

Tommelein, I. & Zouein, P. 1993. Interactive Dynamic Layout Planning. *Journal of Construction Engineering and Management,* 119(2). :266-287.

Tommelein, I.D. 1989. *SightPlan an expert system that models and augments human decision-making for designing construction site layouts. Unpublished thesis.* Stanford University.Ph.D

Tommelein, I.D., Levitt, R. & Hayes-Roth, B. 1992b. Site-Layout Modeling: How can Artificial Intelligence Help? *Journal of Construction Engineering and Management,* 118(3). :594-611.

Tompkins, J.A., White, J.A., Bozer, Y.A. & Tanchoco, J.M.A. 2010. *Facilities planning.* John Wiley & Sons

Van der Merwe, C. & Cheetham, T. 2015. *INFRA SA technical response - SKA.TEL.INFRA-SA.SE-TD-001.* [www.skatelescope.org/wp-content/uploads/2013/09/SKA-TEL-INFRA-SA-SE-TD-001-Rev-1_final.pdf.]

Woodward, J.F. & Woodward, J. 1975. *Quantitative methods in construction management and design.* Macmillan London

Yang, I. 2007. Using Elitist Particle Swarm Optimization to Facilitate Bicriterion Time-Cost Trade-Off Analysis. *Journal of Construction Engineering and Management,* 133(7). :498-505.

Yeh, I. 1995. Construction-Site Layout using Annealed Neural Network. *Journal of Computing in Civil Engineering,* 9(3). :201-208.

Zouein, P. & Tommelein, I. 2001. Improvement Algorithm for Limited Space Scheduling. *Journal of Construction Engineering and Management,* 127(2). :116-124.

Zouein, P. & Tommelein, I. 1999. Dynamic Layout Planning using a Hybrid Incremental Solution Method. *Journal of Construction Engineering and Management,* 125(6). :400-408.

Appendix

Appendix A

Interviewees

The reader should be aware that the people listed below were interviewed in order to get some input and feedback with respect to the work done in this study and therefore in no way should any of the people interviewed be held responsible.

Dawie Le Roux, Junior Site Agent, Resident Engineer on MeerKAT project.   27/ 08/ 2014

▪ *Discussing the construction on SKA;*   28/ 02/ 2015

▪ *Topics: model applications, sequencing,* MeerKAT *& SKA construction, site, practical constraints, activities, resources, equipment, cost rates, quantities, cost drivers.*

NMC (Pty) Civils, 1 Link Close, Montague Gardens

Hennis van Zyl, Area Manager for Lafarge   19/ 02/ 2015

▪ *Discussing the supply of Ready Mix Concrete;*

▪ *Topics: batch plant, truck requirements, delivery, cost components, operational constraints, planning, production, operations.*

Lafarge, Cape Town, 16 Milner Street, Paarden Eiland

Dr GC van Rooyen, Professor of Civil Engineering Informatics   12/ 03/ 2015

▪ *Discussing the model development of site layout planning and repetitive project scheduling;*

▪ *Topics: literature review, model development, optimization algorithms, scheduling methods & models, applications*

Stellenbosch University, Department of Civil Engineering

Jan H van Vuuren, Professor of Operations Research   24/ 02/ 2015

▪ *Discussing optimization techniques and methods;*

▪ *Topics: literature review, metaheuristic optimization algorithms, location and scheduling problem*

Stellenbosch University, Department of Industrial Engineering
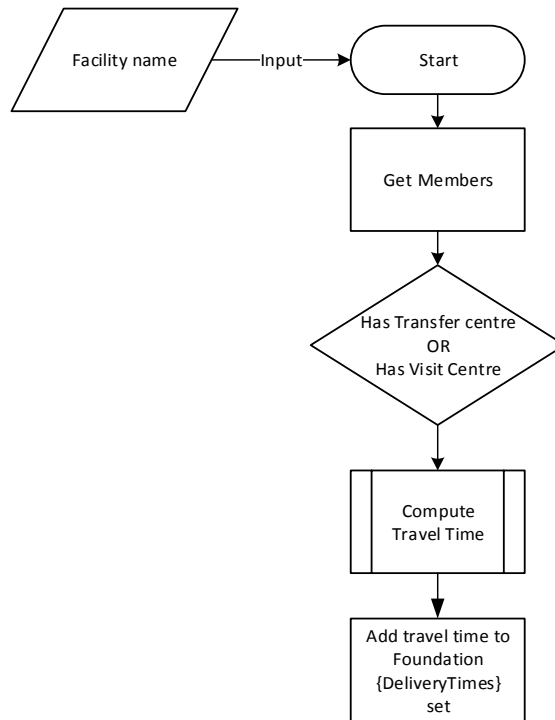
Appendix B

Algorithms utilized in SLP Model
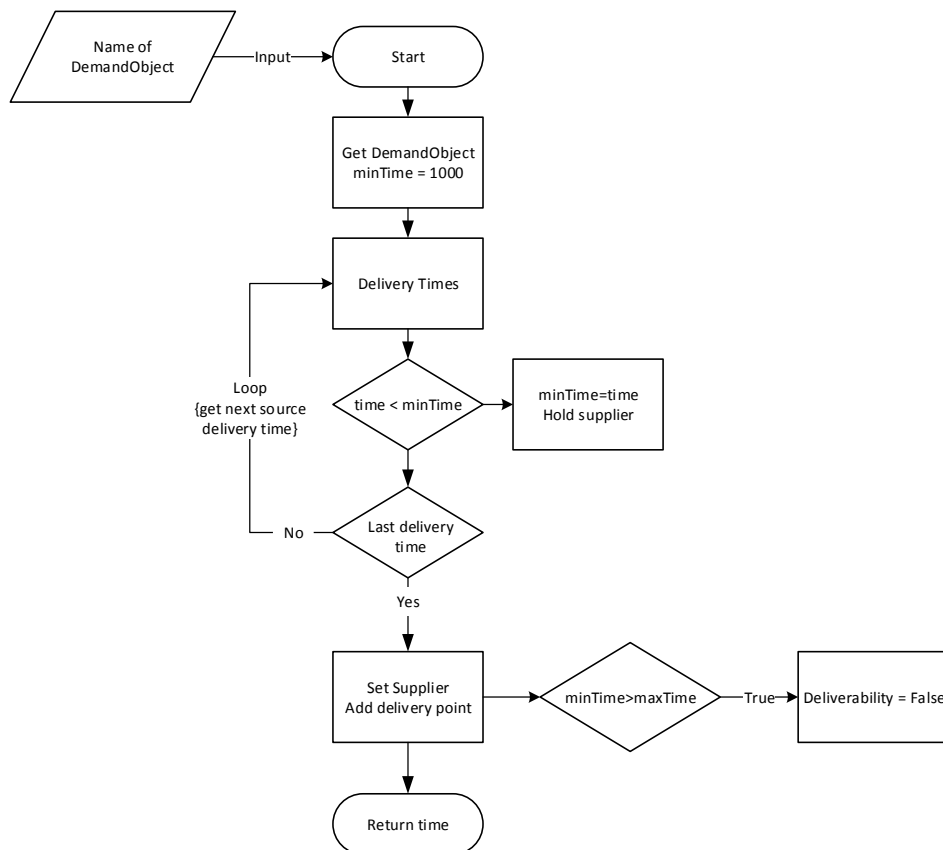

Figure - B.1: Adding Sources-objects to a Foundation

Figure - B.2: Compute minimum supply time for a specific *DemandObject*

Simple site layout planning (SLP) model validation

*Note that F = foundation unit

Table - B.1: Calculating the transport cost from a site camp

Calculating the travel time between sources and demand destinations

```
        *----------------*
--------> For: SiteCamp
--> initialize time matrics for: SiteCamp1(0.00,0.00)
Distance to: F0(5.00,7.00) = 12.00 km; Time = 12.00/(40.0*60) = 18.00 min
Distance to: F1(6.00,7.00) = 13.00 km; Time = 13.00/(40.0*60) = 19.50 min
Distance to: F2(7.00,6.00) = 13.00 km; Time = 13.00/(40.0*60) = 19.50 min
Distance to: F3(7.00,5.00) = 12.00 km; Time = 12.00/(40.0*60) = 18.00 min
Distance to: F4(7.00,4.00) = 11.00 km; Time = 11.00/(40.0*60) = 16.50 min
Distance to: F5(30.00,30.00) = 60.00 km; Time = 60.00/(40.0*60) = 90.00 min
Distance to: F6(40.00,40.00) = 80.00 km; Time = 80.00/(40.0*60) = 120.00 min
Distance to: F7(40.00,40.00) = 80.00 km; Time = 80.00/(40.0*60) = 120.00 min
--> initialize time matrics for: SiteCamp2(-9.10,-13.10)
Distance to: F0(5.00,7.00) = 34.20 km; Time = 34.20/(40.0*60) = 51.30 min
Distance to: F1(6.00,7.00) = 35.20 km; Time = 35.20/(40.0*60) = 52.80 min
Distance to: F2(7.00,6.00) = 35.20 km; Time = 35.20/(40.0*60) = 52.80 min
Distance to: F3(7.00,5.00) = 34.20 km; Time = 34.20/(40.0*60) = 51.30 min
Distance to: F4(7.00,4.00) = 33.20 km; Time = 33.20/(40.0*60) = 49.80 min
Distance to: F5(30.00,30.00) = 82.20 km; Time = 82.20/(40.0*60) = 123.30 min
Distance to: F6(40.00,40.00) = 102.20 km; Time = 102.20/(40.0*60) = 153.30 min
Distance to: F7(40.00,40.00) = 102.20 km; Time = 102.20/(40.0*60) = 153.30 min
--> initialize time matrics for: SiteCamp3(14.10,16.10)
Distance to: F0(5.00,7.00) = 18.20 km; Time = 18.20/(40.0*60) = 27.30 min
Distance to: F1(6.00,7.00) = 17.20 km; Time = 17.20/(40.0*60) = 25.80 min
Distance to: F2(7.00,6.00) = 17.20 km; Time = 17.20/(40.0*60) = 25.80 min
Distance to: F3(7.00,5.00) = 18.20 km; Time = 18.20/(40.0*60) = 27.30 min
Distance to: F4(7.00,4.00) = 19.20 km; Time = 19.20/(40.0*60) = 28.80 min
Distance to: F5(30.00,30.00) = 29.80 km; Time = 29.80/(40.0*60) = 44.70 min
Distance to: F6(40.00,40.00) = 49.80 km; Time = 49.80/(40.0*60) = 74.70 min
Distance to: F7(40.00,40.00) = 49.80 km; Time = 49.80/(40.0*60) = 74.70 min
--> initialize time matrics for: SiteCamp4(-23.10,-16.10)
Distance to: F0(5.00,7.00) = 51.20 km; Time = 51.20/(40.0*60) = 76.80 min
Distance to: F1(6.00,7.00) = 52.20 km; Time = 52.20/(40.0*60) = 78.30 min
Distance to: F2(7.00,6.00) = 52.20 km; Time = 52.20/(40.0*60) = 78.30 min
Distance to: F3(7.00,5.00) = 51.20 km; Time = 51.20/(40.0*60) = 76.80 min
Distance to: F4(7.00,4.00) = 50.20 km; Time = 50.20/(40.0*60) = 75.30 min
Distance to: F5(30.00,30.00) = 99.20 km; Time = 99.20/(40.0*60) = 148.80 min
Distance to: F6(40.00,40.00) = 119.20 km; Time = 119.20/(40.0*60) = 178.80 min
Distance to: F7(40.00,40.00) = 119.20 km; Time = 119.20/(40.0*60) = 178.80 min
```

Summarising time matrix and calculating traveling cost

```
 Time from: [Row;Column] =  [surce;foundations]
[18.00, 19.50, 19.50, 18.00, 16.50, 90.00, 120.00, 120.00]
[51.30, 52.80, 52.80, 51.30, 49.80, 123.30, 153.30, 153.30]
[27.30, 25.80, 25.80, 27.30, 28.80, 44.70, 74.70, 74.70]
[76.80, 78.30, 78.30, 76.80, 75.30, 148.80, 178.80, 178.80]
    Transportation cost for F0[SiteCamp1;18.00] = 128.0 x 18.00 x 4.72 = R 10880.00
    Transportation cost for F1[SiteCamp1;19.50] = 128.0 x 19.50 x 4.72 = R 11786.67
    Transportation cost for F2[SiteCamp1;19.50] = 128.0 x 19.50 x 4.72 = R 11786.67
    Transportation cost for F3[SiteCamp1;18.00] = 128.0 x 18.00 x 4.72 = R 10880.00
    Transportation cost for F4[SiteCamp1;16.50] = 128.0 x 16.50 x 4.72 = R 9973.33
    Transportation cost for F5[SiteCamp3;44.70] = 128.0 x 44.70 x 4.72 = R 27018.67
    Transportation cost for F6[SiteCamp3;74.70] = 128.0 x 74.70 x 4.72 = R 45152.00
    Transportation cost for F7[SiteCamp3;74.70] = 128.0 x 74.70 x 4.72 = R 45152.00
      *--------------*
```

Table - B.2: Calculating the total transfer time for a demand

Supply Demand

```
Cycle time: 15.0+18.00+10.0 = 43.00 min
SupplyFinishedTime: Batchplant2-F0: 43.00x3.0+45.0 = 174.00 min
Cycle time: 15.0+21.00+10.0 = 46.00 min
SupplyFinishedTime: Batchplant2-F1: 46.00x3.0+45.0 = 183.00 min
Cycle time: 15.0+21.00+10.0 = 46.00 min
SupplyFinishedTime: Batchplant2-F2: 46.00x3.0+45.0 = 183.00 min
Cycle time: 15.0+18.00+10.0 = 43.00 min
SupplyFinishedTime: Batchplant2-F3: 43.00x3.0+45.0 = 174.00 min
Cycle time: 15.0+15.00+10.0 = 40.00 min
SupplyFinishedTime: Batchplant2-F4: 40.00x3.0+45.0 = 165.00 min
Cycle time: 15.0+162.00+10.0 = 187.00 min
SupplyFinishedTime: Batchplant2-F5: 187.00x3.0+45.0 = 606.00 min
Cycle time: 15.0+222.00+10.0 = 247.00 min
SupplyFinishedTime: Batchplant2-F6: 247.00x3.0+45.0 = 786.00 min
Cycle time: 15.0+222.00+10.0 = 247.00 min
SupplyFinishedTime: Batchplant2-F7: 247.00x3.0+45.0 = 786.00 min
```

Visit Demand

```
Cycle time: 10.0+36.00+10.0 = 56.00 min
VisitFinishedTime: SiteCamp1-F0: 56.00x4.0 = 224.00 min
Cycle time: 10.0+39.00+10.0 = 59.00 min
VisitFinishedTime: SiteCamp1-F1: 59.00x4.0 = 236.00 min
Cycle time: 10.0+39.00+10.0 = 59.00 min
VisitFinishedTime: SiteCamp1-F2: 59.00x4.0 = 236.00 min
Cycle time: 10.0+36.00+10.0 = 56.00 min
VisitFinishedTime: SiteCamp1-F3: 56.00x4.0 = 224.00 min
Cycle time: 10.0+33.00+10.0 = 53.00 min
VisitFinishedTime: SiteCamp1-F4: 53.00x4.0 = 212.00 min
```

Table - B.3: Calculating ready mix concrete truck requirements for batch plant

```
    ->Truck requierments for:Batchplant2
F0 requiers Min[5;12] = 5 trucks
F1 requiers Min[5;12] = 5 trucks
F2 requiers Min[5;12] = 5 trucks
F3 requiers Min[5;12] = 5 trucks
F4 requiers Min[4;12] = 4 trucks
F5 requiers Min[19;12] = 12 trucks
F6 requiers Min[25;12] = 12 trucks
F7 requiers Min[25;12] = 12 trucks
```

Appendix C

Algorithms utilized in RPS Model

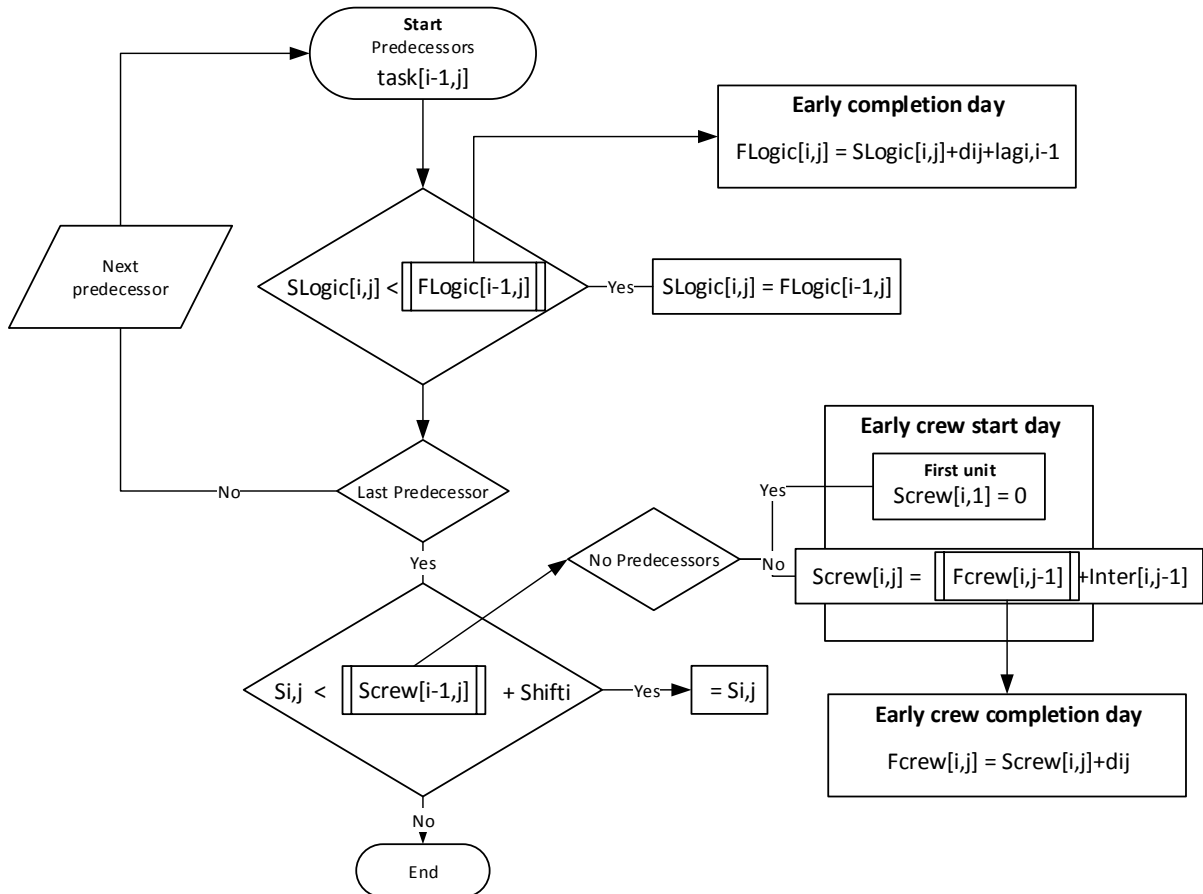The implementation of the algorithm calculating the early start of and *Task* in the RPS model is shown below:

Figure - C.1: Algorithm calculating activity early start.
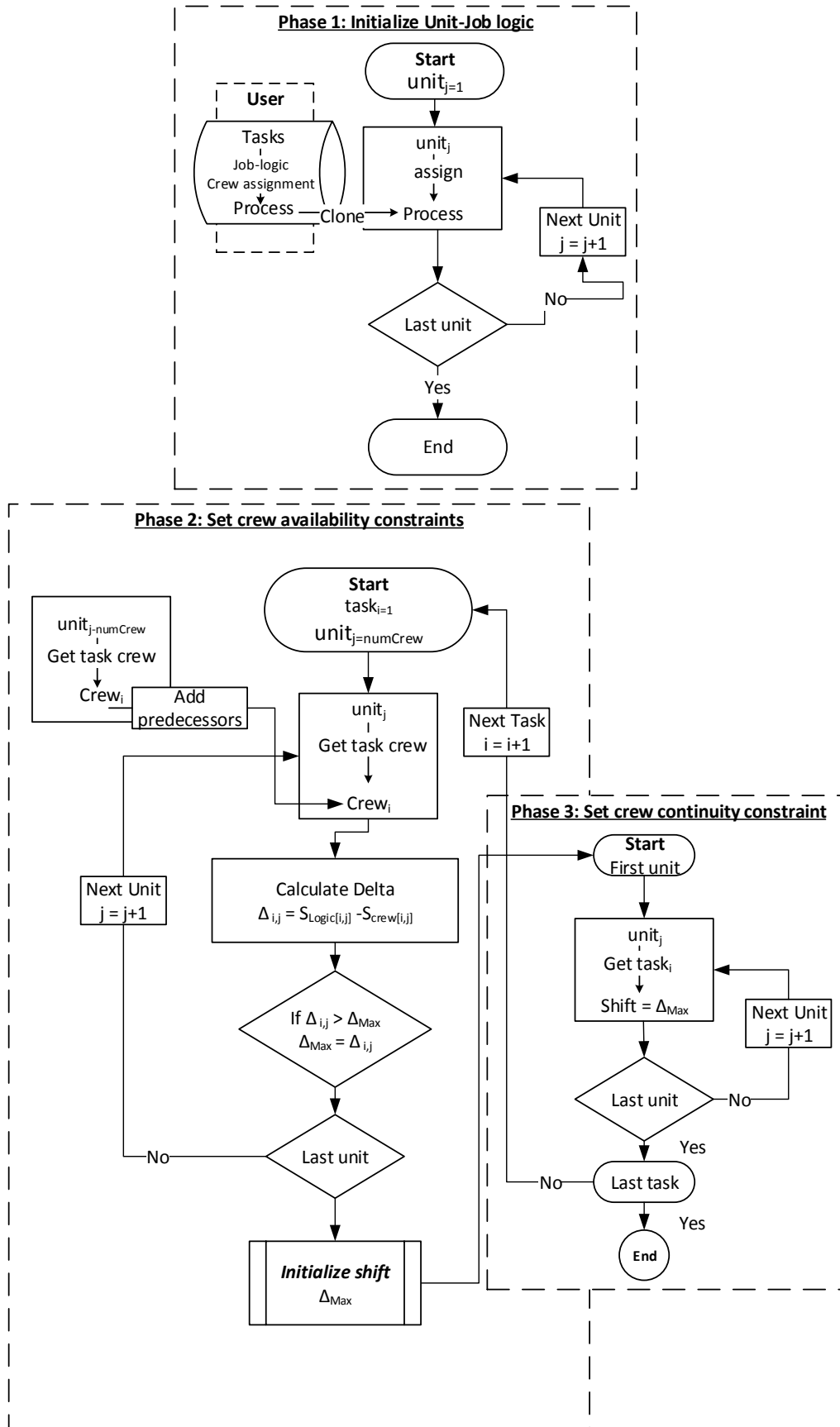
Figure - C.2: Scheduling algorithm

Repetitive project scheduling (RPS) model validation

Table - C.1: Initializing the activity duration update for long resource travel times

```
     --->F5; time:89.40 min; x= 0.19
PreparePileSteelCages: 2.68 < 2.00 > 5.37
Drill: 2.68 < 2.00 > 5.37
Pilling: 2.68 < 1.00 > 5.37
Excavate: 2.68 < 4.00 > 5.37
>>>>Update:F5-Excavate = 5
Earthing: 2.68 < 1.00 > 5.37
Blinding-SteelFixing-Shutters: 2.68 < 3.00 > 5.37
>>>>Update:F5-Blinding-SteelFixing-Shutters = 4
Concrete: 2.68 < 1.00 > 5.37
Remove shutters: 2.68 < 1.00 > 5.37
```

**Table - C.2: Calculating resource continuity shift**

```
--Compute Shift for: PreparePileSteelCage    --Compute Shift for: Earthing--
----> 0                                       0-|22-0 = 22|-
-InitializeShift-                             1-|26-1 = 25|-
--Compute Shift for: Drill--                  2-|30-2 = 28|-
0-|2-0 = 2|-                                   3-|34-3 = 31|-
1-|4-2 = 2|-                                   4-|38-4 = 34|-
2-|6-4 = 2|-                                   5-|43-5 = 38|-
3-|8-6 = 2|-                                   6-|47-6 = 41|-
4-|10-8 = 2|-                                  7-|51-7 = 44|-
5-|12-10 = 2|-                                 ----> 44
6-|15-12 = 3|-                                 -InitializeShift-
7-|18-15 = 3|-                                 --Compute Shift for: Blinding-SteelFixing-Shutters--
----> 3                                        0-|45-0 = 45|-
-InitializeShift-                              1-|46-3 = 43|-
--Compute Shift for: Pilling--                 2-|47-6 = 41|-
0-|5-0 = 5|-                                    3-|48-9 = 39|-
1-|7-1 = 6|-                                    4-|49-12 = 37|-
2-|9-2 = 7|-                                    5-|50-15 = 35|-
3-|11-3 = 8|-                                   6-|51-19 = 32|-
4-|13-4 = 9|-                                   7-|52-23 = 29|-
5-|15-5 = 10|-                                  ----> 45
6-|18-6 = 12|-                                  -InitializeShift-
7-|21-7 = 14|-                                  --Compute Shift for: Concrete--
----> 14                                        0-|48-0 = 48|-
-InitializeShift-                              1-|51-1 = 50|-
--Compute Shift for: Excavate--                2-|54-2 = 52|-
0-|18-0 = 18|-                                  3-|57-3 = 54|-
1-|19-4 = 15|-                                  4-|60-4 = 56|-
2-|20-8 = 12|-                                  5-|64-5 = 59|-
3-|21-12 = 9|-                                  6-|68-6 = 62|-
4-|22-16 = 6|-                                  7-|72-7 = 65|-
5-|23-20 = 3|-                                  ----> 65
6-|25-25 = 0|-                                  -InitializeShift-
7-|29-29 = 0|-                                  --Compute Shift for: Remove shutters--
----> 18                                        0-|69-0 = 69|-
-InitializeShift-                              1-|70-1 = 69|-
                                               2-|71-2 = 69|-
                                               3-|72-3 = 69|-
                                               4-|73-4 = 69|-
                                               5-|74-5 = 69|-
                                               6-|75-6 = 69|-
                                               7-|76-7 = 69|-
                                               ----> 69
                                               -InitializeShift-
```

Table - C.3: Scheduling activities of repetitive units

```
-PreparePileSteelCages-          -Earthing-
F0: 0<->2                        F0: 44<->45
F1: 2<->4                        F1: 45<->46
F2: 4<->6                        F2: 46<->47
F3: 6<->8                        F3: 47<->48
F4: 8<->10                       F4: 48<->49
F5: 10<->12                      F5: 49<->50
F6: 12<->15                      F6: 50<->51
F7: 15<->18                      F7: 51<->52
-Drill-                          -Blinding-SteelFixing-Shutters-
F0: 3<->5                        F0: 45<->48
F1: 5<->7                        F1: 48<->51
F2: 7<->9                        F2: 51<->54
F3: 9<->11                       F3: 54<->57
F4: 11<->13                      F4: 57<->60
F5: 13<->15                      F5: 60<->64
F6: 15<->18                      F6: 64<->68
F7: 18<->21                      F7: 68<->72
-Pilling-                        -Concrete-
F0: 14<->18                      F0: 65<->69
F1: 15<->19                      F1: 66<->70
F2: 16<->20                      F2: 67<->71
F3: 17<->21                      F3: 68<->72
F4: 18<->22                      F4: 69<->73
F5: 19<->23                      F5: 70<->74
F6: 20<->24                      F6: 71<->75
F7: 21<->25                      F7: 72<->76
-Excavate-                       -Remove shutters-
F0: 18<->22                      F0: 69<->70
F1: 22<->26                      F1: 70<->71
F2: 26<->30                      F2: 71<->72
F3: 30<->34                      F3: 72<->73
F4: 34<->38                      F4: 73<->74
F5: 38<->43                      F5: 74<->75
F6: 43<->47                      F6: 75<->76
F7: 47<->51                      F7: 76<->77
```
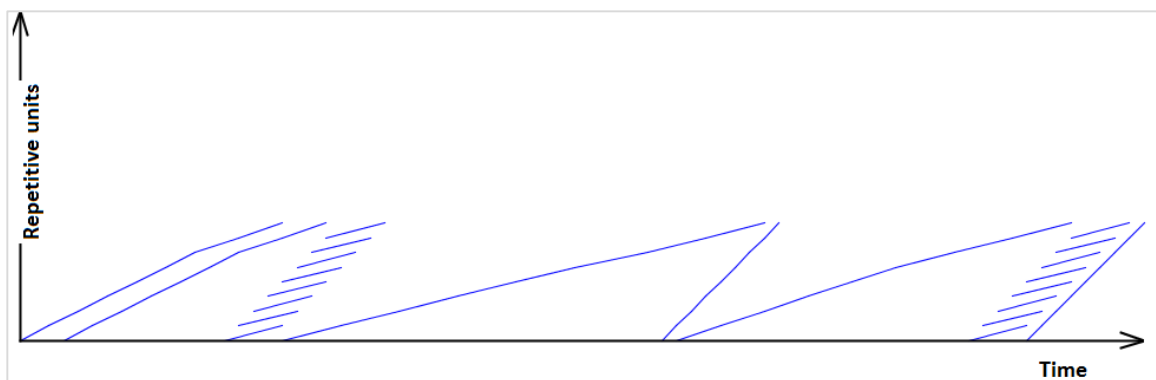

Note: activity production curves are no longer straight due to the activity duration update
Figure - C.3: Production curve schedule after initializing activity duration update

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Appendix D

Summarising the unique concept in the model formulation

The unique concept behind formulating the model to integrate space, time and logistics is summarised here. Firstly, space refers to the location of temporary construction facilities and work destinations on site. Secondly, time refers to the duration of construction activities and the physical scheduling thereof. Thirdly, logistics refers to the planning of the on-site material handling. How this integration is formulated is summarised by the graphical visual representation in Figure 10.2. Figure 10.2 is supplemented with an explanatory numbered list that matches the numbered items in the Figure in order to guide the reader through the process. Although the model was developed for antenna foundation units, the same approach and modelling concept can be used for other repetitive projects, as discussed in (1) in the explanatory list below:
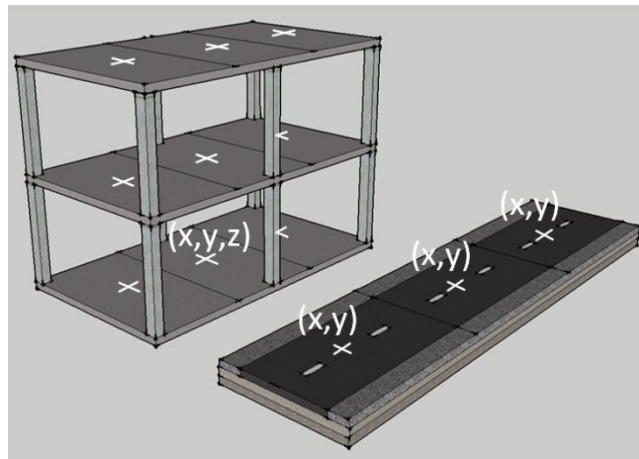
Figure 10.1: Context to other repetitive projects

1. These are destinations on site that require a specific set of construction activities, resources and material to complete the scope of works at that location. Various types of demand destinations can be included in the SLP model. Therefore the same concept can be applied to, for example, road construction project as shown in Figure 10.1.

2. This is the specific sequence of construction activities that must be performed in order to complete the scope of works at the specific location on site.

3. The activities in (2) constitute the repetitive process assigned to all demand destinations that require the same activities. For example the construction of an antenna foundation will require a different repetitive process from the construction of a road section.

4. Each activity has both a resource and material demand and can be different from one another. Demand destinations can also be of different types (i.e. antenna foundation and road section), requiring different resources and material.

5   These are the crew formation, labour and equipment required to perform the work of a construction activity.

6   These are the construction materials required, dependent on the design of the structure.

7   This is the object that connects temporary construction facilities on site with demand destinations for the supply of material, equipment and resources. In this illustration concrete is used.

8   Temporary construction facilities must be established on site to support the construction operations at demand destinations. There might be multiple sources that support the same operation. Therefore this is a group of facilities on site of the same type which supports same operation.

9   This is a source for the supply of a specific demand on site.

10 In this case a batch plant facility is used which supplies concrete to an antenna foundation unit.

11 These are the attributes that belong to a specific temporary construction facility. As soon as a source (construction facility) is added on site it inherits these attributes called FacilityTraits.

12 Once the model executes, each individual DemandObject belonging to the demand destinations on site is linked to the appropriate sources on site. It is here where the dynamic flow of resources are determined.

13 The flow of resources are subject to practical constraints on site, for example in the case where one must access a site gate in order to reach the demand destinations.

14 This is the object connecting temporary construction facilities and demand destination on site. It can be assigned many attributes in order to retrieve information from the model.

The model uses this unique framework to integrate space, time and logistics.
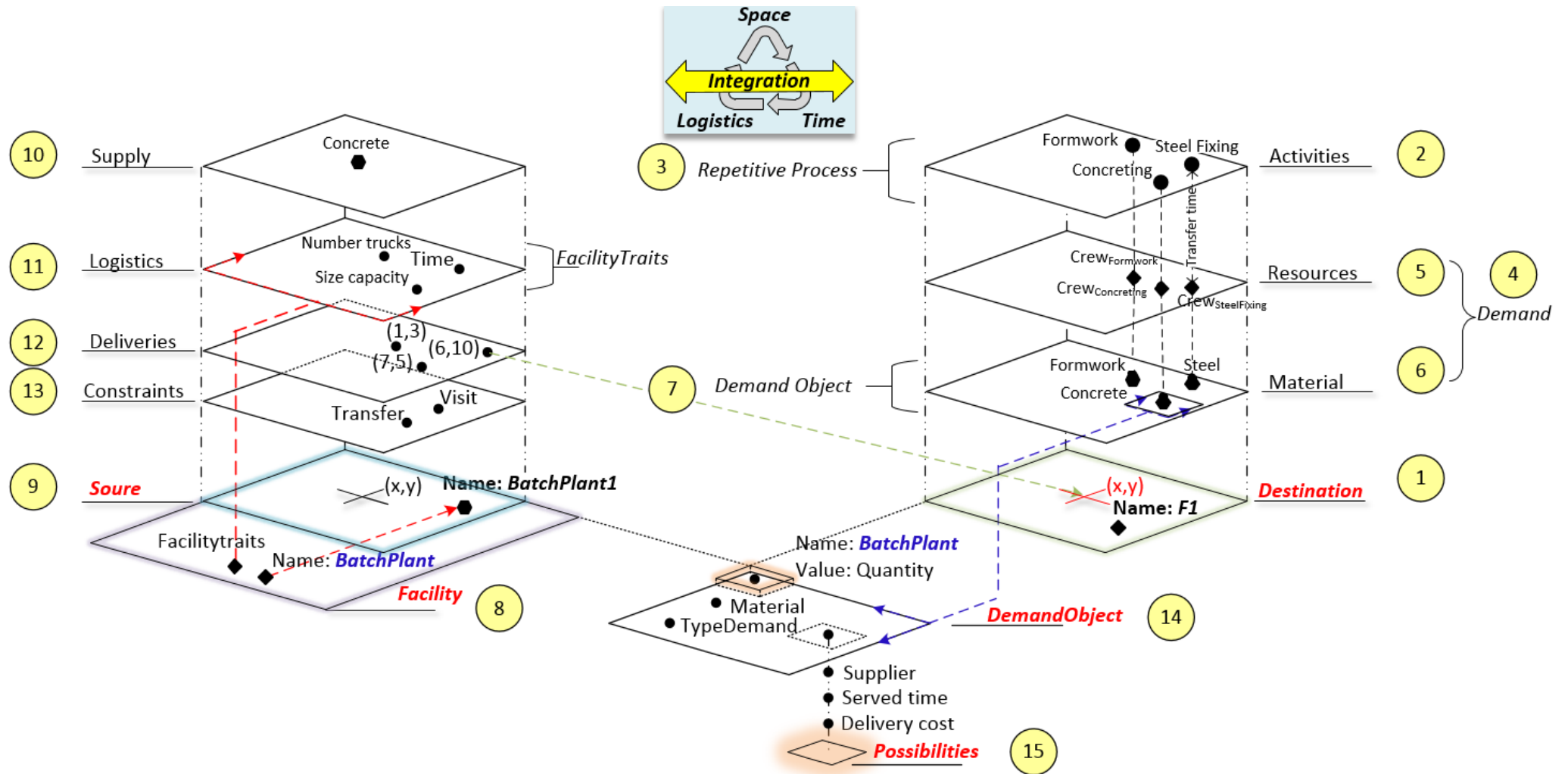
Figure 10.2: Graphic visual representation of modelling concept

Appendix E

Fictitious SKA example
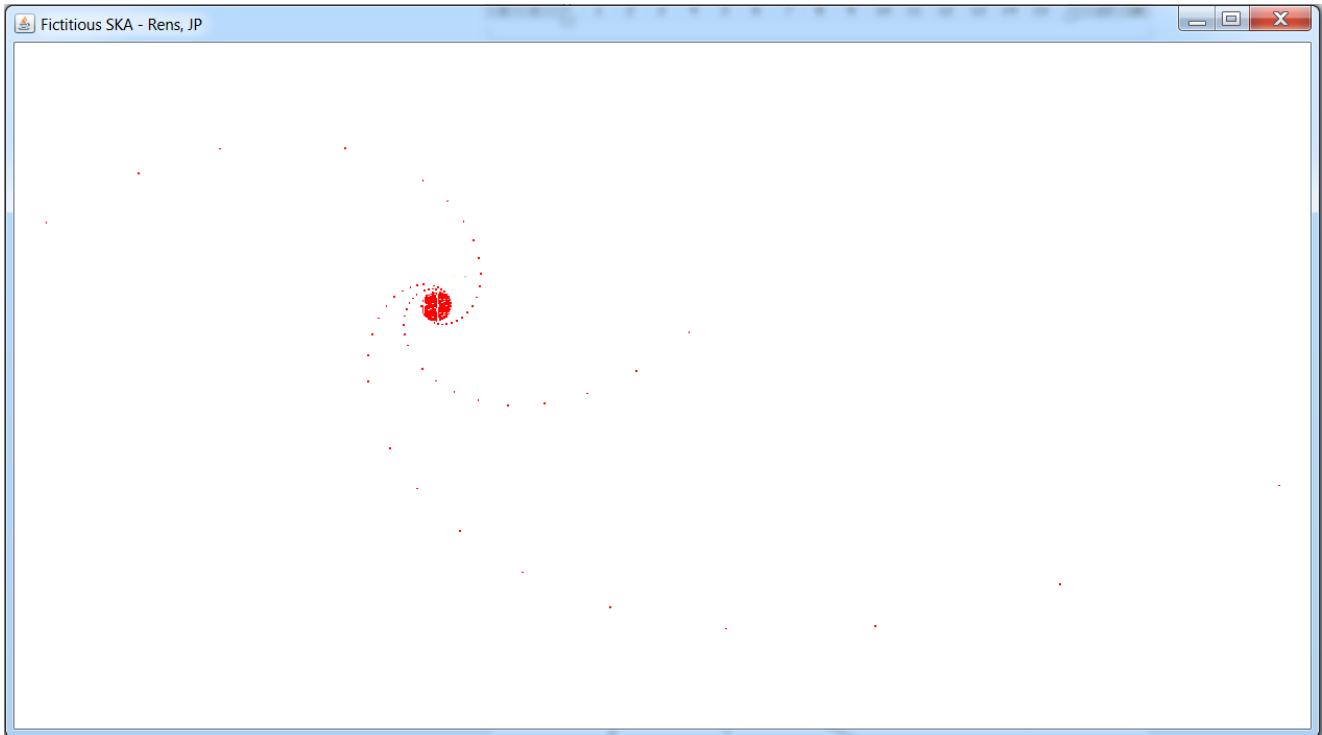
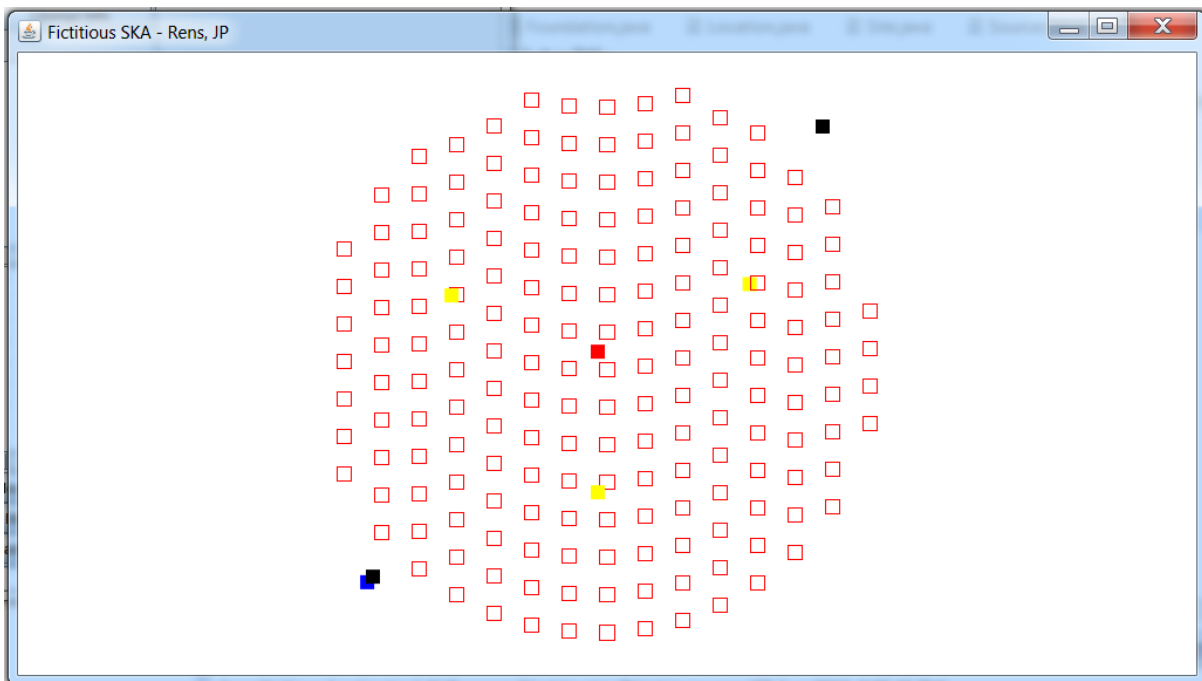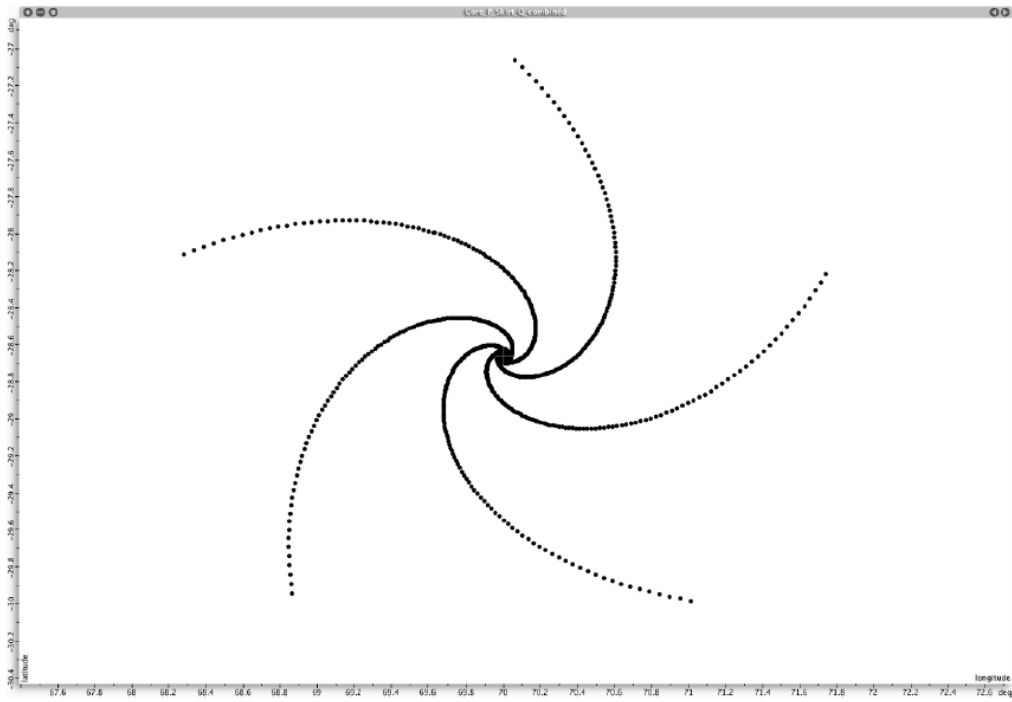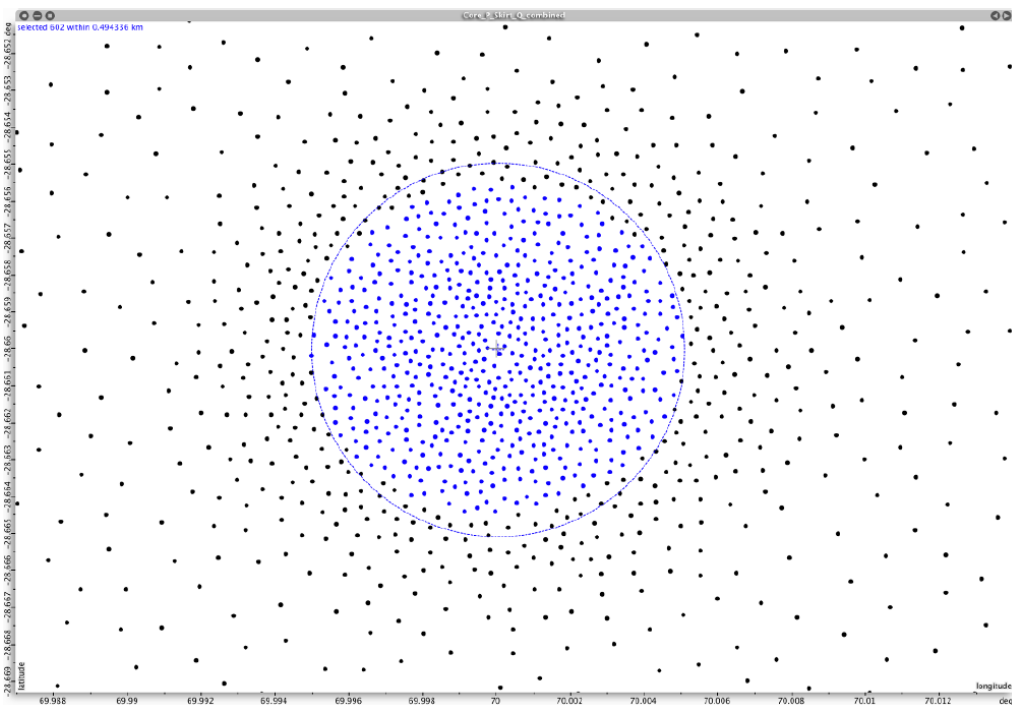**Figure - E.1: The SLP model graphical view of fictitious SKA project**

Figure - E.2: The SLP model graphical view of central region of fictitious SKA project

Figure - E.3: Whole layout of 2400 dishes extending to 180km from the centre (Millenaar & Bolton, 2010)

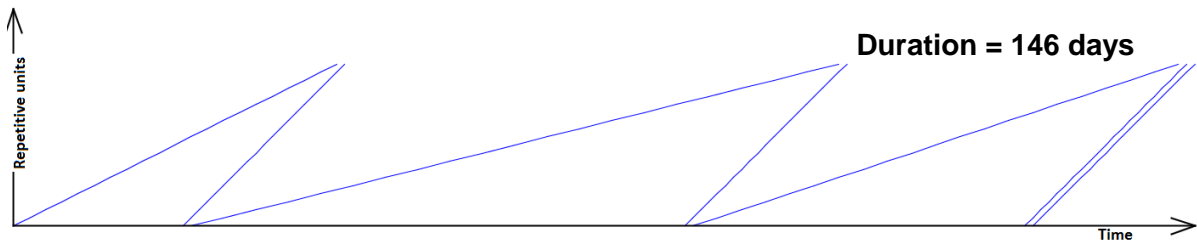**Figure - E.4: The inner core. The circle is 1km in diameter (Millenaar & Bolton, 2010)**

Figure - E.5: Introductory example schedule 1
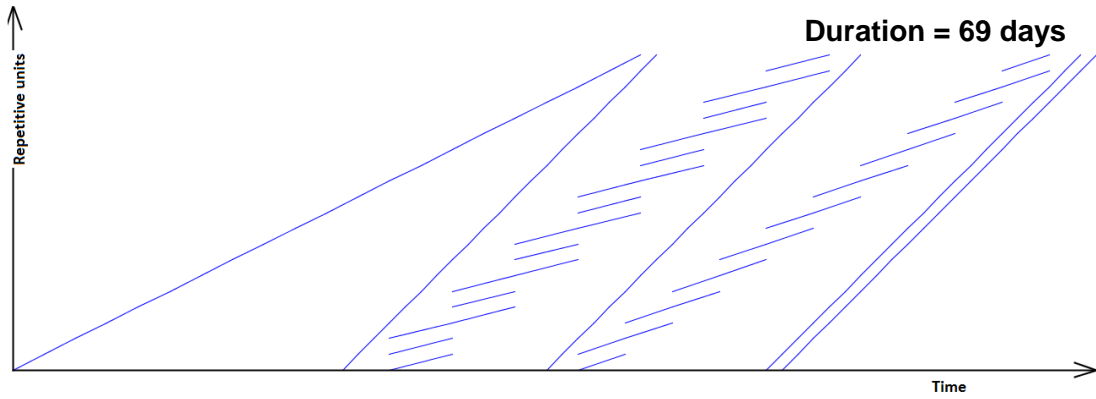
Figure - E.6: Introductory example schedule 2
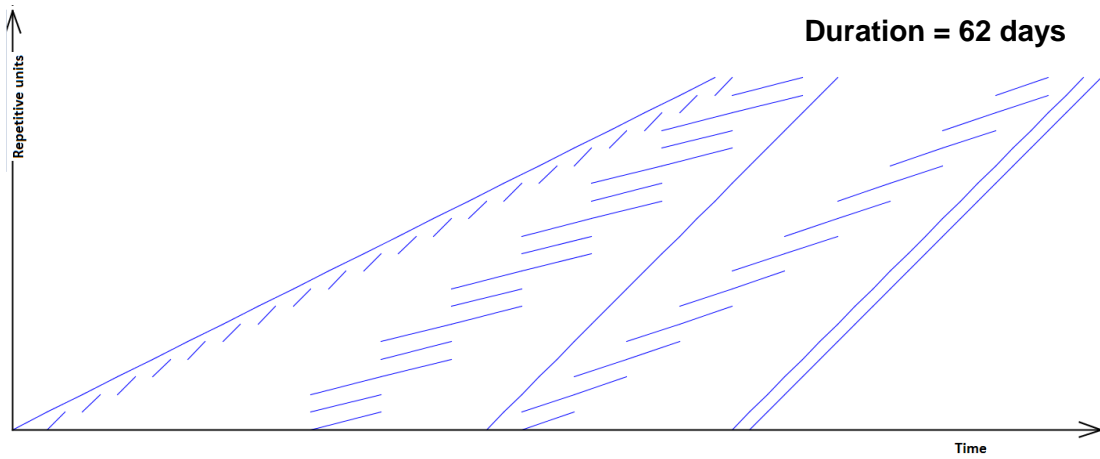
Figure - E.7: Introductory example schedule 3
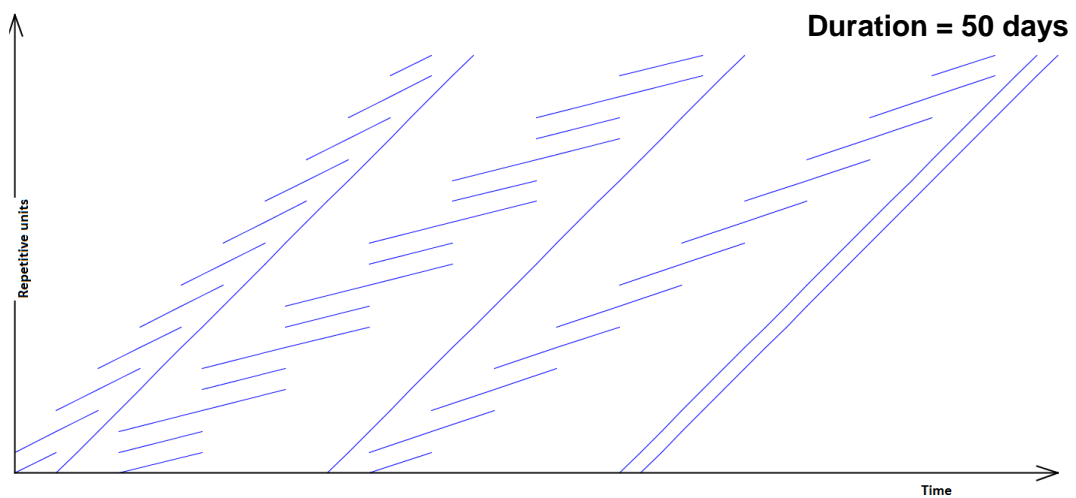
Figure - E.8: Introductory example schedule 4

Appendix F

Cost Assumptions

All the estimated elements listed in this section was assumed for the purpose of executing the models developed in this study on a fictitious SKA project.

Table - F.1: Temporary construction facility information

Facility Traits\Facility Name	Batch Plant	Steel fabrication yard	Storage yard	Site camp
Dimensions (mxm)	100 x 200	100 x 50	100 x 100	50 x50
Install cost (Rand)	R 700 000	R 2250 000	R 50 000	R 200 000
Number of trucks	4	1	1	1
Truck volume	6	3	2	1
Truck hire cost	0 R/hour*	250R/hour	250 R/hour	150 R/hour
Facility operating time (hours)	5	5	8	8
Load time (min)	15	30	15	15
Unloading time (min)	10	30	20	10
Max delivery time (min)	120	240	240	120
Colour	black	blue	green	grey

*included by supplier

Table - F.2: Antenna foundation material demand

Foundation Demand					Building material		
Name:	*Quantity*	*Material*	*Demand Type*		Name:	Rate	Unit
Batch Plant	72 m^3	concrete	*supplyDemand*		concrete	R 1300	m^3
Steel fabrication yard	8 cages	steel	supplyDemand		steel	R 4500	ton
Storage yard	4 trips	Equipment+ steel	*visitDemand*				
Site camp	4 trips	resources	visitDemand				

Table - F.3: Equipment and material cost rates

| Equipment			Labour	
Item	Rate (R/hour)		Item	Rate (R/hour)
Ready mix concrete truck	0*		Skilled labour	26.8
Pilling Rig	1500		Skilled labour	32.1
Digger Loader	250		Skilled labour	53.5
Dumper truck	450		Ganger	32.1
Crane	600		Operator	0*
Steel reinforcement truck	250			

*included by supplier

Appendix G

User Manual for GUI

Following below is a description of the different components on the MainView of the GUI and what the functionality of each is. Table - G.1 presents an introduction to the detailed step-by-step explanation entailing the procedure required to customize the site layout. The column titled "*Box*" in Table - G.1 indicates to the delimited dashed red boxes in Figure 6.2 and Figure 6.3, in §6.2. The column titled "*Ref*" in Table - G.1 indicates to a screenshot that illustrates the associated display on the MainView. Reference is made to these pictures (picture A to I) with delimited dashed red boxes in order to supplement the explanation.

Table - G.1: Explanatory list of GUI component functionality

| Box	Component	Functionality	Ref
1	AuxView	This is the view that changes according to the instruction given by the user in the MainView.	--
2	Command Prompt	This window prompts the user with instructions if a wrong selection has been made	[G]
3	Source Model	This is a model that contains all the facilities on site	--
4	Destination Model	This is a model that contains all demand destinations on site	--
5	Assumptions	Press to retrieve Assumptions. Can then Change	[A]
5	Add Source	Either select "Add source" or "Add foundation"	[B]
6	Selection Model	This is a model that contains the facilities that have been created and ready to be added to the site	--
5	"Add" with "Add source" selected	Select a facility in Box 6 and press to add a facility of that type to the construction site	[C]
5	"Add" with "Add Destination" selected	Select Foundation in Box 6 and press to add a Foundation destination to the site	[D]
5	Change Info	Select a facility in Box 6 and press to change the facility characteristics.	--
5	Add Facility	Press to create a new facility for customization reasons. Once a facility is created it is added as a facility object in Box 6, ready to be added to the construction site	[E] [F]

| 7	Remove selected	Select a source in Box 3 and press to remove the selected source from the construction site	--
7	Change or move	Select a source in Box 3 and press to move the source to different position on site. or to add constraints to the selected source	[G]
9	Add Constraint	Specify if the constraint is either a transfer centre or visit centre.	[H]
_	Specify constraint type	Transfer centre has been added as a constraint to Batch plant 1	[I]
8	Run Simulation	Press to run the simulation and measure the effectiveness of the site layout and generate a project schedule. The site layout and schedule graphical view (visual representation) is also provided.	--
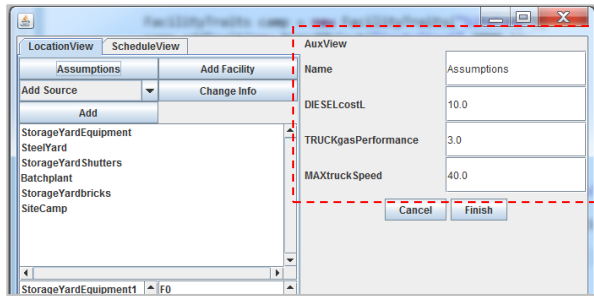
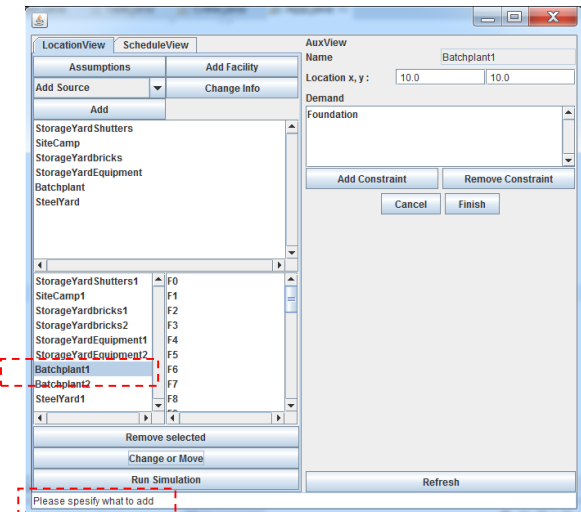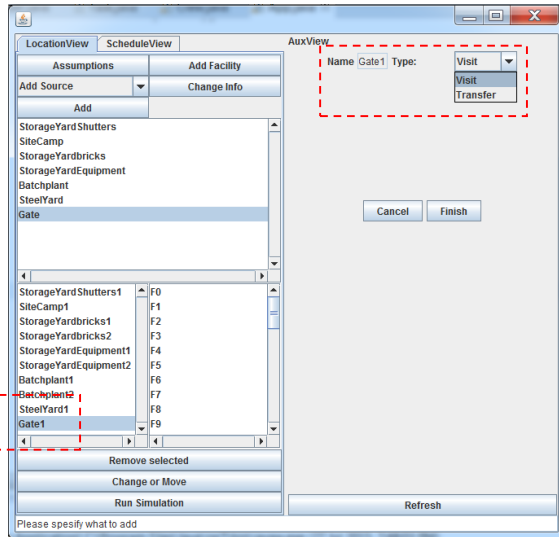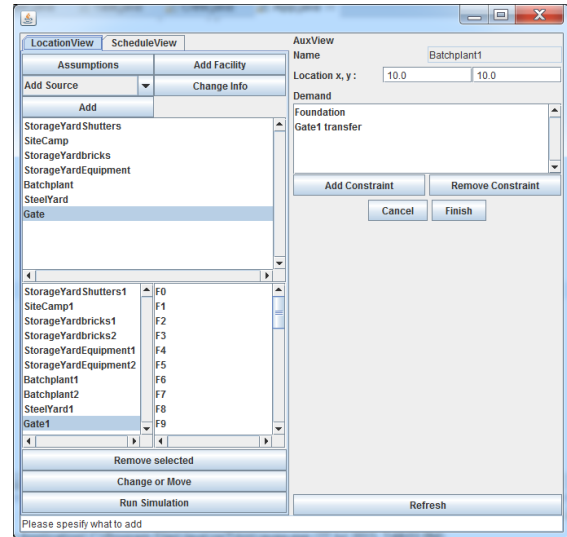[A]
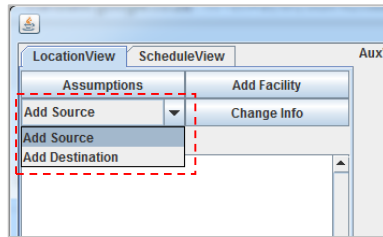
[B]
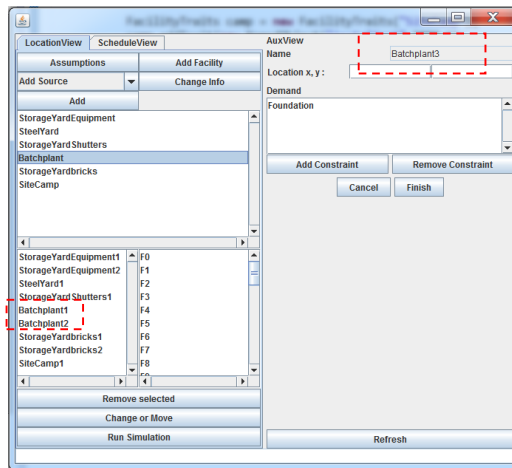
[C]
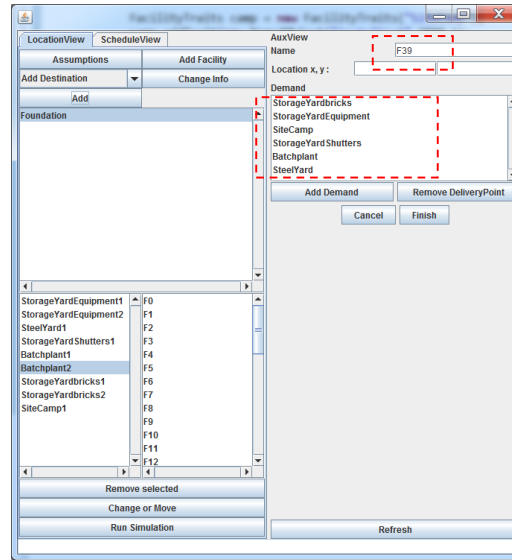
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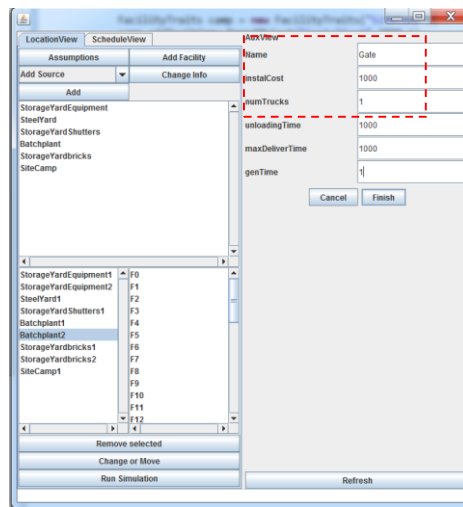
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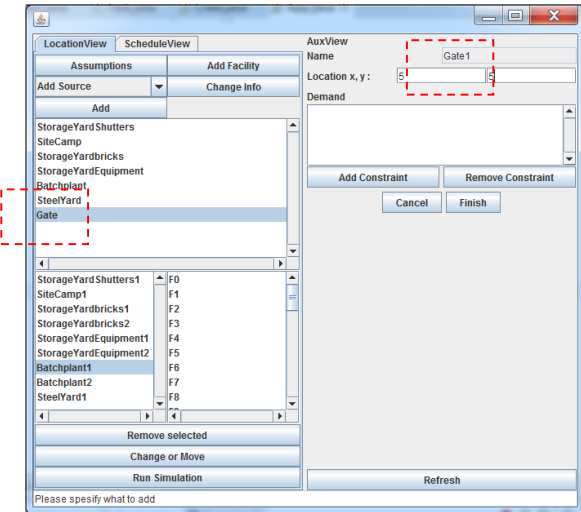
[F]

[G]

[H]   **[I]**

Appendix H

SLP mode and RPS model UML diagram

The UML diagram of the construction deployment planning model (site layout planning (SLP and repetitive project scheduling (RPS) model)) developed is this study as well as the GUI and schedule and site visualization view is shown on the next page.

Figure - H.1: UML diagram of the construction deployment planning model