Determining the Tractor Fleet Size in an Underground Coal Mine through Simulation Modelling

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Declaration

I declare that this project report is my own, unaided work, except where otherwise acknowledged. The research was conducted under the ethical requirements as laid out by the University Main Ethics Committee (non-medical), with the ethics clearance number: MIAEC 094/21. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

Signed this 12th day of May 20 22

Alexander Michiel Malan.

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Abstract

Sasol Mining is moving from its current three shift system, containing two 10 hour production shifts and an overlapping 10 hour maintenance shift (excluding weekends), to full calender operations. Under the full calender operations there are two 12 hour production shifts along with a six hour window shift for every day of the week. This enables the Sasol Mining complex to keep up with the 40mt/pa demand from its Secunda factory. This new shift system positions each mine for 24 hour production.

The problem considered in this project is that of determining the effect of the full calender operations on the tractor fleet size by designing, developing, validating and implementing a simulation model depicting the different processes and variables at the mine. The objectives pursued in this project is (1) to determine how the move to 24 hour operations affect the tractor support services, and (2) to make a recommendation to the Bosjesspruit mine regarding their tractor fleet size based on output from the simulation model.

A systematic approach in the design and development of a simulation study is followed in the development of the simulation model. The simulation model output is validated through the use of equivalence testing. The results obtained through the equivalence tests confirm that the model is an accurate representation of the tractor operations at the Bosjesspruit mine.

The simulation model output provides a clear indication of the impact that the implementation of the full calender operations will have on the tractor support services at the Bosjesspruit mine. Based on the output analysis, the Bosjesspruit tractor fleet will not be able to perform at the current level under the full calender operations.

This model serves as a tool for decision making in a very high pressure and uncertain operating environment. By mitigating the risks associated with testing different scenarios in the real-world operations at the mine, the model enables the testing of different scenarios. Based on the analysis of these scenarios, it is recommended that the tractor fleet is pooled and that additional shifts are utilised over weekends. This will enable the Bosjesspruit mine to reduce its tractor fleet, whilst improving the performance of the tractor support services.

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1 Introduction

1.1 Project Background

Coal is one of the most infamous and widely accessible natural resources across the globe. It is primarily used as a fuel source in electric power generation. Even though the environmental impact of this fossil fuel is cause for alarm, it still accounts for approximately 40% of electricity generation worldwide (Burnard and Bhattacharya, 2011). It is clear that its importance as a resource cannot be disputed. However, the focus of this project is not on the uses of coal or its environmental effects, but rather on the activities associated with the mining of coal deposits.

1.1.1 Coal Mining

A coal seam is formed over thousands of years from the combination of biota, minerals and natural chemicals. Compression, along with heat, sedimentation, erosion, and chemical energy act as the facilitators in the forming processes of coal. Coal can be divided into different classes dependent on the stage of its formation, as shown in Figure 1.1. Coal mining takes place within these seams or deposits in order to extract the resource for use (Schissler, 2004).

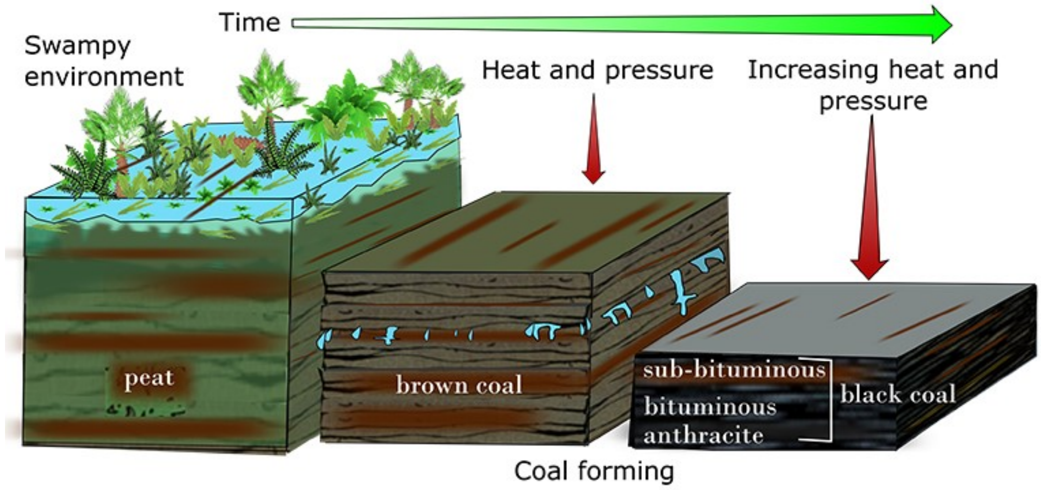

Figure 1.1: A representation of the formation of a coal seam (Geoscience Australia, 2021)

The mining of coal deposits has been done for hundreds of years, with Europe having first mined coal deposits over 700 years ago (Thomas, 2013). Historically coal mining had been dominated by the UK and European countries like Germany. In 1900, Europe and the UK produced a combined total of 422,4 million tonnes of coal. This accounted for more than 60% of global production.This dominance gradually decreased at the start of the 20th century when reliance on coal and its production slowed in Europe and the UK, causing a major shift in the coal mining industry. The USA overtook the UK as the biggest producer of coal worldwide, and countries outside of Europe like China, Russia, Australia and South Africa all saw a major and consistent increase in their annual coal production (Daemen, 2004). In 2000, Europe and the UK produced a combined total of 176,4 million tonnes, less than 5% of the global production which totalled 3639 million tonnes (Daemen, 2004).

Technological advances in mining methods as well as mining equipment and machinery have enabled an increase in production capacity from the top producing countries in the industry. In 2019, the combined coal production worldwide totalled 7953 million tonnes. China has in recent years cemented its position as the top coal producing country, accounting for approximately 46% of the total production in 2019 (International Energy Agency, 2020).

Coal mining takes place in numerous countries, but the methods used are very similar and can be easily classified.

The mining of coal can be divided into two broad categories *viz.* surface mining and underground mining. Traditionally, underground mining dominated the coal mining industry, but with the advances in the equipment and machinery used in surface mining this balance has shifted. In the US for example, surface mining accounts for approximately two thirds of the total coal production (Daemen, 2004). The method used is dependent on the geology as well as other factors that can be unique to each area considered for coal mining.

Surface Mining

Surface mining, can in itself be divided into two broad categories *viz.* strip mining and open cast mining. However, these follow the same principles of coal extraction. The coal seam is accessed from the surface by firstly removing any vegetation, then through the removal of material above the seam, referred to as the overburden. The overburden is removed through the use of explosives that fracture the overburden before it can be removed by machinery in order to reveal the coal seam (Schissler, 2004, Thomas, 2013).

In strip mining, the overburden is removed in rectangular blocks adjacent to each other, called strips. The overburden is removed and handled by the same equipment used in the mining process. As the overburden is removed, it is deposited in an adjacent strip that has already been mined. This exposes the coal seam and mining activities can commence, and the cycle is then repeated until the maximum amount of coal has been recovered from the area. This is illustrated in Figure 1.2. Strip mining is used along the outcrop of a coal seam or a number of seams (Thomas, 2013)

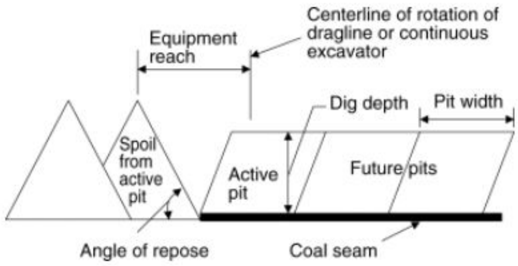

Figure 1.2: A graphical illustration of a strip mining process (Schissler, 2004)
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Open cast mining, sometimes referred to as area mining, is less elongated and requires the overburden to be moved away from the working area and deposited in a dedicated area at a different location. Figure 1.3 shows a open cast coal mine in South Africa. The difference between strip mining and open cast mining lies in the handling of the overburden. In open cast mining the overburden must be transported to a nearby site through the use of a truck fleet or a conveyor system before the coal seam can be mined (Balasubramanian, 2016, Thomas, 2013).

Figure 1.3: An open cast mine in Limpopo, South Africa (KH Plant, 2021)
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Several factors need to be considered before a decision can be made to make use of surface mining methods in coal extraction. However, most of these relate to the depth and thickness of the coal seam. Generally, from a physical and economic standpoint, the most important factor relates to the depth of the coal seam and the amount of overburden. Physically, limitations with regards to machine capabilities must be considered. Whilst economically, the stripping ratio serves as an early indication of economic feasibility. The stripping ratio refers to the ratio expressing the volume of overburden that needs to be removed in order to produce one tonne of coal (Falkie and Porter, 1973).

Underground Mining

If practical limitations or an undesired stripping ratio eliminates the more economical surface mining methods, underground mining is used to extract coal from deposits (Schissler, 2004). For an underground mining operation, a number of activities have to be accomplished in order to access the coal seam. The first involves shaft sinking and/or creating an adit to reach the coal seam lying beneath the surface. Then roadways must be developed underground in order to reach the working faces, referred to as panels. Once these panels are accessible, extraction can begin through one of two methods. These are known as longwall mining and room and pillar mining. Once the mine is operational, provisions must be made for support services required for sustained production (Thomas, 2013).

Longwall mining is a relatively new method of underground mining, only developed over the last 50 years. Longwall mining aims to provide full extraction of a panel with high levels of automation. This is executed by dividing the mining area into elongated panels that are accessed from a roadway, previously developed by continuous miners. The panels are then mined by a single machine called the longwall, completing all the functions required in the extraction process, including coal cutting and providing temporary support through the use of hydraulic shields.This process is shown in Figure 1.4 below. As the longwall advances, the temporary support is removed and the roof is allowed to collapse (Balasubramanian, 2016, Thomas, 2013).

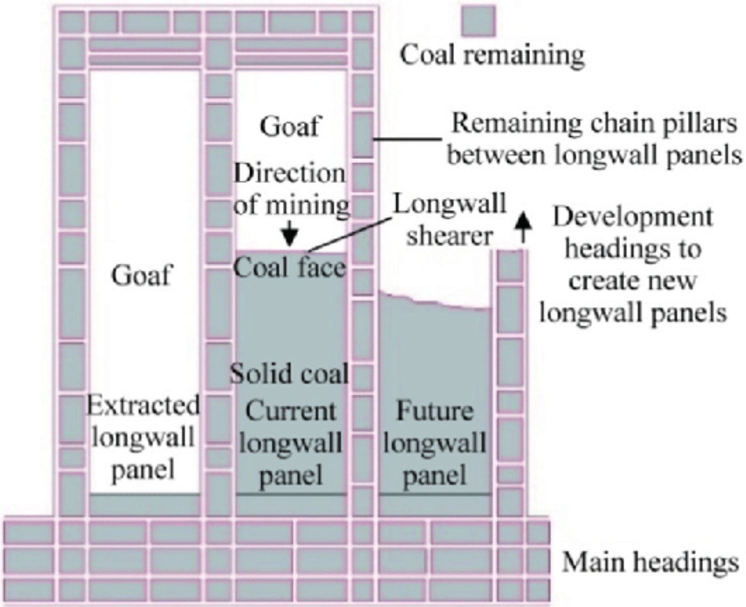

Figure 1.4: Diagram depicting a longwall mining operation (Vardar et al., 2018)

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Room and pillar mining is a widely used underground mining method. The basic methodology is that coal is extracted in rectangular rooms, whilst pillars left between rooms act as the main source of roof support. This method of mining results in a pattern similar to a chess board. In room and pillar mining, only partial extraction can be achieved as the remaining pillars are required for roof support.

The coal can be extracted through one of two methods. The first is referred to as conventional mining. This involves the drilling and blasting of the coal face. The second method, known as continuous mining, has a machine called the continuous miner fitted with cutting drums. The continuous miner is the more widely used method, as it provides a higher production rate. Another important piece of equipment is the roof bolter, providing secondary roof support in areas where coal has been extracted. Shuttle cars and feeder breakers are responsible for the transportation of coal from the working face to underground conveyors. Figure 1.5, shows a room and pillar mining operation with a continuous miner. The extraction of coal is done in a sequence that allows the mine to expand horizontally, as the rooms are used as travel and supply routes in the mine, enabling constant access for production support services (Balasubramanian, 2016, Thomas, 2013).

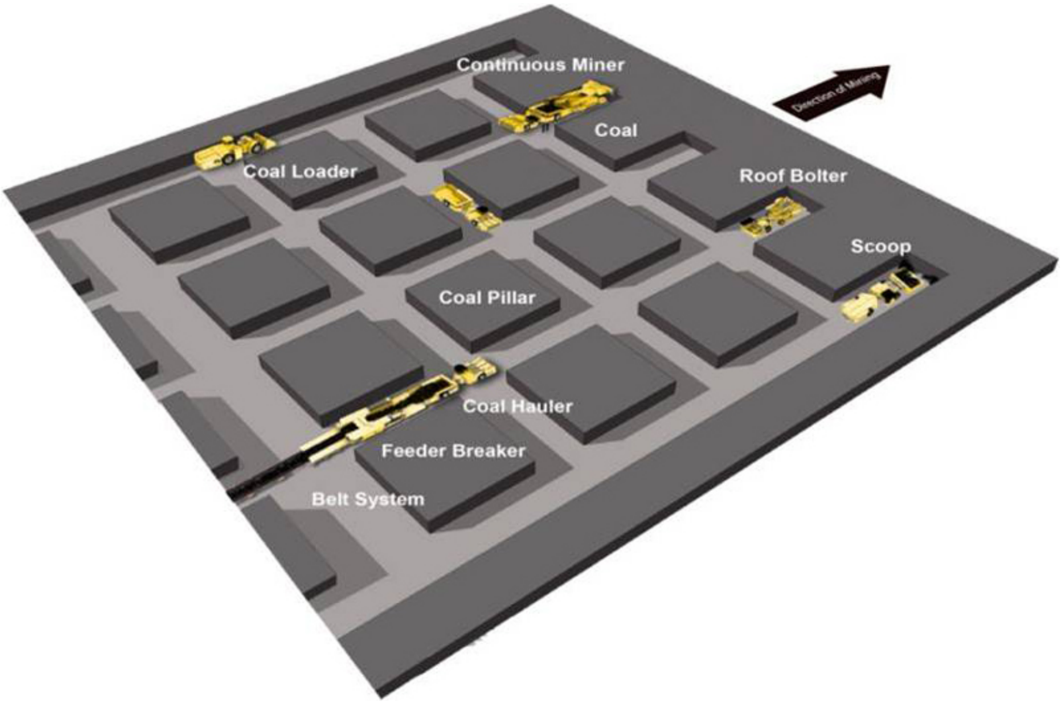

Figure 1.5: Diagram depicting a room and pillar mining operation (Caterpillar Global Mining, 2021)

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1.1.2 Coal Mining in South Africa

South Africa is a major player in the global coal mining industry. In a 2010 report, the country ranked 7th in terms of total production, with 247 million tonnes per annum and 5th for coal exports at 67 million tonnes per annum (Eberhard, 2011).

The role of coal in the South African economy cannot be understated. In 2016, South Africa exported approximately a third of its coal production to international markets through the Richards Bay Coal Terminal. These exports accounted for R112 billion worth of sales, a valuable source of foreign exchange. Domestically, South Africa's power utility Eskom, uses its 16 coal power plants to generate approximately 82% of the total domestic electricity supply. Electricity generation accounts for roughly 53% of domestic coal demand. Apart from electricity, the iron and steel sector accounts for about 20%, whilst synthetic fuels and chemical industries make up a further 10% of local demand, with the remaining demand stemming from various smaller industries (Chamber of Mines of South Africa, 2018).

According to the Mineral Council of South Africa (Minerals Council South Africa, 2021), the coal industry provides direct employment to 92 000 people, representing a significant portion of the total employment provided through different mining activities. Furthermore, they report that in 2019 the industry spent R61 billion in the procurement of services and goods. As most of this investment is on a local level, the coal industry indirectly provides thousands of jobs in various industries. This is a vital contribution in a country struggling with high levels of unemployment.

Although mining activity takes place in several provinces in South Africa, the vast majority of coal mining takes place within the Mpumalanga province, consisting of the Witbank, Highveld and Ermelo coal fields (Eberhard, 2011).

A number of large companies have dominated the coal mining industry in South Africa, employing both surface and underground mining methods. In a 2010 study, five companies accounted for almost 80% of the total coal production. These were Anglo-American, Exxaro, Sasol Mining, BHP Billiton and Xstrata (Eberhard, 2011).

1.1.3 Sasol Mining

Sasol is a multinational energy and chemicals company, operating in over 30 countries and regions. Sasol successfully operates the only coal-to-liquids fuel production facilities in the world, shown in Figure 1.6 below. The Secunda Synfuels Operations, located in Secunda, Mpumalanga, South Africa are capable of producing 160 000 barrels of petroleum per day. This represents a major share of the total production capacity in South Africa. In order to sustain this level of production, the Secunda Synfuels Operations requires around 40 million tonnes of coal per annum (Eberhard, 2011). To satisfy this demand, Sasol operates five underground coal mines in the Secunda area. [1] The Isibonelo mine, also provides coal to the Secunda Synfuels Operations in a long standing agreement. However, this mine is operated by Anglo-American.

Figure 1.6: The Sasol Secunda Synfuels Operations, Mpumalanga, South Africa (IOL, 2019)

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The five mines are: Thubelisha, Impumelelo, Syferfontein Colliery consisting of three shafts, Shondoni and lastly, the Bosjesspruit colliery through its Irenedale shaft. The five underground mines utilise the room and pillar method, with continuous miners in order to meet their respective production targets.

As a result of shortcomings in production yield across the five Secunda mines in recent years. Sasol Mining has had to spend a large amount of capital on purchasing coal from external suppliers. In order to mitigate the expenses incurred by buying in coal, production has to be increased. Sasol

[1] The company also operates the Mooikraal mine near Sasolburg, Free State. However, coal produced from this mine is not used at the Secunda Synfuels Operations.

Mining currently employs a three shift system comprising of two 10 hour production shifts as well as an overlapping 10 hour maintenance shift (excluding weekends where the Saturday has one production shift and the Sunday is reserved for maintenance). A decision was made to implement a new shift system.

In order to keep up with the 40mt/pa demand from the Secunda Synfuels Operations, Sasol Mining is moving to full calendar operations (referred to as Fulco). This new shift system has two 12 hour production shifts along with a six hour window shift for every day of the week. This enables 24 hour production across the mines in the Sasol Mining Complex. This increases production capacity and reduces the need to spend capital on coal from external suppliers. A graphical representation of the two shift systems and their differences is provided in Figure 1.7 below.

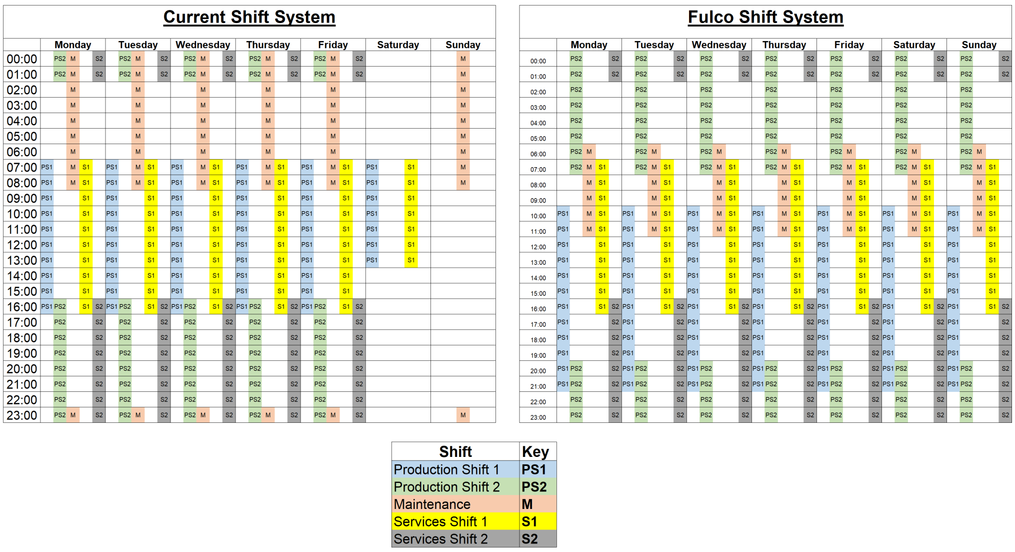

Figure 1.7: Sasol Mining Shift Systems

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1.2 Problem Statement

Sasol Mining is moving from its current three shift system to full calender operations, commonly referred to as Fulco. This enables the Sasol Mining complex to keep up with the 40mt/pa demand from the Secunda factory. This new shift system positions each mine for 24 hour production.

The implementation of Fulco and the changes associated with its execution will affect each colliery in a unique manner. These changes are broad and affect more than just production. A critical enabler of 24 hour production is reliable and constant support services. The associated support services must also adapt to the new system. Amongst the various support services are those that utilise tractors in its execution. An example of a tractor used in rendering these support services is shown in Figure 1.8 below.

Figure 1.8: Flameproof underground tractor (Birdmachines, 2021)

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As with any piece of equipment, these require significant capital investment and operational expenditure. A management decision on the number of tractors to be used in support of production activities is required at the respective mines.

Currently a simplified calculation is used across the Sasol Mines to determine the respective tractor fleet requirement of each mine. However, due to the costs associated with owning and operating the equipment, there is a need for a more accurate method. The aim of this project is to determine the tractor fleet size by taking into account the specific needs that the fleet must fulfil, as well as the mine specific conditions. These will be used as input to build a dynamic simulation model that can be used in a case study at the Bosjesspruit mine. At the Bosjesspruit Colliery, Irenedale shaft, there will be a reduction in the number of production sections at the shaft. This reduction along with the implementation of the Fulco shift system, has an impact on the support services and the tractor fleet requirements.

1.3 Research Question

How can a simulation model with both academic and practical rigour, be used to determine the tractor fleet size considering the effect of the Fulco operations on the tractor fleet and the support services they provide at the Bosjesspruit mine, Irenedale shaft?

1.4 Project Objectives

The objectives of this research are:

I To *understand* the nature of the problem and *investigate* different solution approaches by *conducting* a thorough literature review related to:

   (a) The fleet sizing problem
   (b) The categorising of the fleet sizing problem
   (c) The solution approaches to the fleet sizing problem
   (d) The application of the fleet sizing problem in different industries.

II To *investigate* the current as-is operation of the tractor fleet in order to understand the operating environment.

III To *model* the current system at the Bosjesspruit mine with the chosen simulation method.

IV To *verify* and *validate* the model according to generally accepted guidelines.

V To *apply* the model to different scenarios under the Fulco shift system.

VI To *evaluate* the results of the model and provide a recommendation on the tractor fleet size and management policy to the various stakeholders.

VII To *recommend* sensible follow-up work related to the work in this project which may be pursued in the future.

2 Literature Review

The problem described in §1.2, is one where the number of vehicles (tractors) required to perform the operations within a business is unknown. An informed management decision needs to be made to address the problem. The decision must ensure that the vehicle fleet has enough capacity to meet the operational demand, whilst also ensuring that the capital costs associated with these resources are minimised. This question gives rise to a type of problem found in various real-world situations, described in literature as the *fleet sizing problem*.

The chapter opens in §2.1 with an introduction to the fleet sizing problem. In §2.2, the reader is introduced to the different ways the fleet sizing problem can be categorised. Then in §2.3, the various methods that can be utilised to solve the fleet sizing problem are discussed. Finally, to illustrate the versatility of the fleet sizing problem, in §2.4 an overview of some of the applications of the fleet sizing problem in different industries is provided. The chapter is summarized in §2.5.

2.1 The Fleet Sizing Problem

Within companies operating a fleet of vehicles, the strategic and tactical decisions made regarding this fleet are of great value to the business. The fleet management of any organisation comprises of a number of different areas. These include, amongst others, defining the fleet composition, the assignment and routing of vehicles as well as the maintenance strategy (Zak et al., 2008). In defining the fleet composition, an important strategic decision is the number of vehicles in the fleet, known as the fleet sizing problem.

As noted by Parikh (1977), in simple terms, the fleet sizing problem seeks to answer the question of determining the number of vehicles [1] required in order to fulfil an operational need with a known demand, or one that can be determined probabilistically. In essence, the focus of the problem is matching the supply and demand within a company. Here supply refers to the number of vehicles available, whilst the demand is concerned with the amount and frequency of tasks that need to be completed by these vehicles. Importantly, the fleet sizing problem aims to balance the fixed costs associated with the ownership and operation of such a fleet, with the high cost of not meeting the operational demand (Zak et al., 2008). Beaujon and Turnquist (1991) likens this to a similar problem encountered by businesses in their inventory management policy. The various costs of holding inventory needs to be weighed against the cost of not being able to meet customer demand as a result of a stock out.

2.2 Categorising the Fleet Sizing Problem

In order to choose the appropriate solution methodology, the fleet sizing problem can be classified in a number of different ways to understand the complexity of the problem at hand.

There are various different factors that affect the way that the fleet sizing problem is categorised. Turnquist and Jordan (1986) propose a simple classification scheme dependent on two factors. The first is the traffic pattern encountered by the fleet. This often determines the complexity of the problem as it can be a simple formulation of movements from one point of origin to one destination, or very complex with multiple points of origin and multiple destinations. The next factor is based on the shipment size, where the importance is the movement of full or partial loads.

[1] The term vehicle refers to any resource that forms part of a collection of similar resources and collectively used to satisfy some operational requirement within a company.

Zak et al. (2008) build on work conducted by Dejax and Crainic (1987) to propose a more concise set of classification criteria. It is summarised into four categories. The first is loaded or empty flows, whether the problem is limited to the movement of loaded vehicles or includes the movement of empty vehicles. The second is unimodal and multimodal transportation, that is, more than one transportation mode considered in the problem formulation. Thirdly the fleet composition, whether it is homogeneous or heterogeneous. And finally, the industry or environment in which the problem occurs.

Dejax and Crainic (1987) also state that another way to categorise a fleet sizing problem is determined by the characteristics of the problem itself. The problem under consideration can be classified as static or dynamic when considering the time domain, or deterministic or stochastic depending on the nature of demands and input data.

2.3 Solution Approaches in the Fleet Sizing Problem

According to Zak et al. (2008), three major solution approaches to the fleet sizing problem exist: analytical methods, optimisation methods and simulation methods. These are explained in more detail in the following subsections.

2.3.1 Analytical Methods

Friedenthal et al. (2012) describe an analytical model as being quantitative or computational in its nature, where the problem under investigation can be represented by a set of mathematical equations. These equations, once formulated, can be used to answer specific questions or aid decision making. In simple terms, an analytical model is a mathematical model into which data is loaded for analysis (Turban et al., 2010). In analytical models, the goal is to create a mathematical abstraction of the real-world problem.

Analytical models can be divided into static and dynamic models. A static model is one that is independent of time and the parameters of the analytic model do not vary with time. On the other hand, a dynamic model is an analytical model that includes the time-varying components of the system under consideration (Friedenthal et al., 2012). The representation of a problem with an analytical model can be either deterministic or stochastic. This is dependent on whether uncertainties encountered in the problem under consideration need to be incorporated in the representative mathematical equations. If so, uncertainties or randomness are introduced through stochastic modelling.

Turnquist and Jordan (1986) formulate a container fleet sizing problem as an analytical model. The containers are used in an automotive manufacturing plant. In order to determine the fleet size, they consider the number of containers at each stage of the production process. At the component plant, the number of containers is represented by an equation determining the minimum amount of containers required to hold one production cycle of parts. At the assembly plant, the number of containers is dependent on the specified inventory levels of the different parts. The last stage considered represents containers in transit. Here an equation incorporates both container movements and travel times. The fleet size is calculated by the summing of each of these individual calculations. This is shown for illustrative purposes in equation 2.1 below.

$$S = (\frac{1}{p})[\Lambda(L-\tau)-\phi^{-1}(P).751(\sum_{i=1}^{n}\lambda_i^2\sigma_i)^{1/2})+\sum_{i=1}^{n}\lambda_i(2\mu_i+\eta_i+1.75\sqrt{\sigma_i})]. \quad (2.1)$$

Here, S denotes the container fleet size. The first portion of the equation $((\frac{1}{p})[\Lambda(L-\tau)-\phi^{-1}(P).751(\sum_{i=1}^{n}\lambda_i^2\sigma_i)^{1/2})$ considers the container movements. The latter $(\sum_{i=1}^{n}\lambda_i(2\mu_i+\eta_i+1.75\sqrt{\sigma_i})])$ denotes the travel times. Individual components within this equation are described in detail by Turnquist and Jordan (1986). By incorporating uncertainties in the variables at the different stages, Turnquist and Jordan (1986) propose both a deterministic and a stochastic model in determining the container fleet size.

A fleet sizing problem involving both laser guided vehicles and pallet shuttles operating in conjunction in a warehouse is approached with an analytical model by (Ferrara et al., 2014). The model proposed by the authors seeks to calculate the workload of both vehicle fleets operating in the warehouse, whilst stochastically introducing the variability associated with their respective service times. The calculation used by the authors is shown in equation 2.2.

$$U_L GV = r_a \frac{\bar{T}_S^{LGV}}{k}. \tag{2.2}$$

The utilization (workload) of the laser guided vehicles is represented by $U_L GV$. Whilst $\bar{T}_S^{LGV}$ denotes the mean and the variance of the total laser guided vehicle service time. Furthermore, r_a represents the arrival rate of handling orders and k the number of laser guided vehicles. A queuing model is then applied in order to determine the level of utilization required for the pallet shuttle fleet. Based on this, the fleet sizes for the different vehicles can be determined.

Du and Hall (1997) approach a fleet sizing problem by building on knowledge in the field of inventory theory. Using this as a basis, they are able to model the problem analytically and determine the optimal fleet size. This model is built on a decentralised operating policy, similar to that used in inventory control systems (Du and Hall, 1997).

Apart from those highlighted in this section, various other authors have used analytical models in solving the fleet sizing problem. However, this approach is not always viable for the problem under investigation. As the complexity of the model increases, the amount of computational power required to get to a solution greatly increases. In this case, alternative solution approaches should be investigated (Law, 2015).

2.3.2 Optimisation Methods

Optimisation models seek to provide an optimal value to a complex equation. This value, either a minimum or a maximum, is often constrained by limits within the variables contained in the equation. These constraints reflect the real-world limitations of the problem investigated. Dejax and Crainic (1987) state that there are various optimisation solution techniques for the fleet sizing problem. These include mathematical programming (linear, non-linear and integer) optimisation and heuristics.

Optimisation through the use of linear programming seeks to find the minimum or maximum value of a simple function, referred to as the objective function. This function is subject to certain constraints invoked on it during the formulation of the problem. In linear programming no variables can be raised to higher powers (Britannica, 2017). The simplex method is a widely used tool for solving linear programming models. Several authors have used linear programming in order to solve the fleet sizing problem. Choobineh et al. (2012) encounter a fleet sizing problem where the number of AGVs need to be determined in a manufacturing or distribution environment. The authors describe the behaviour of the system as a closed queuing network. This queuing network is then modelled by a linear program, where the objective function, describing the utilization required to fulfil the system demands, is minimised. The value returned in the minimisation of the objective function, shown in equation 2.3, is the optimal number of AGVs.

$$AGV = \text{Minimise}\left(\sum_{(i,j)\epsilon L}\rho_i j^L \sum_{(i,j)\epsilon U}\rho_i j^U \sum_{(i,j)\epsilon I}\rho_i j^I \sum_{(i,j)\epsilon O}\rho_i j^O\right). \qquad (2.3)$$

This equation is subject to constraints considering different elements within the manufacturing environment. These include the throughput of the loading station and the throughput of the loaded travel processors. Wu et al. (2005) provide another example of linear programming used in the fleet sizing problem. They explicitly model various operational and tactical decisions in the truck-rental industry as a linear programming model in order to determine the optimal fleet size.

Non-linear programming models allow for non-linear variables in both the objective function or the constraints of the problem. This can be essential for accurately depicting the real-world problem. Beaujon and Turnquist (1991) apply a non-linear programming model for the fleet sizing problem with a homogeneous fleet. The authors initially formulated the problem in terms of the expected values of random variables (stochastic model). This initial model was then transformed into a non-linear network optimisation problem (deterministic model), with the objective function being maximised to obtain the maximum profit. In this case the profit refers to the difference between the revenue and transportation costs of operating a given fleet size. In order to solve the non-linear programming model, Beaujon and Turnquist (1991) made use of an interactive search procedure based on a Frank–Wolfe algorithm.

Both linear and non-linear programming assume that the variables contained in their formulation are continuous. In integer programming models, the restriction is that all variables must be integer values. This is often a realistic representation of a real-world scenario as some variables cannot be represented by non-integer values. In their investigation of a fleet sizing problem at a container terminal, Vis et al. (2005) seek to minimise the vehicle fleet size. They model the problem as an integer programming model with time-window constraints. The solution to this model provides the authors with the minimum number of vehicles to perform operations at the container terminal.

An alternative to mathematical programming models is the use of heuristics. The word “heuristic” originates from a Greek word, roughly translated, it means to discover. The aim of a heuristic is to systematically search the solution space of a problem to obtain an acceptable solution (Zanakis and Evans, 1981). Heuristics have been successfully applied to complex optimisation problems. A heuristic solution approach consists of applying one of the many well known optimisation heuristics, including evolutionary algorithms, neural networks, genetic algorithms, tabu search and many others (Winker and Gilli, 2004). Sayarshad and Ghoseiri (2009) use an evolutionary algorithm, called simulated annealing. The authors investigate a fleet sizing problem in the rail industry. The simulated annealing algorithm used to determine the optimal fleet size was proven to be acceptable when validated with numerical examples. In a fleet size and mix problem, Renaud and Boctor (2001) propose a novel heuristic called a sweep-based algorithm in their attempts to determine the optimal fleet size. Another example of a heuristic approach to the fleet sizing problem is the tabu search algorithm used by Brandão (2007) to solve another fleet size and mix problem.

There are other optimisation techniques that have also been successfully applied to the fleet sizing problem. These include amongst others multi-objective optimisation (Zak et al., 2008). However, the discussion is limited to optimisation techniques that are frequently encountered in literature and proven successful when attempting to solve different fleet sizing problems.

2.3.3 Simulation Methods

The analytical and optimisation techniques described in the previous sections can provide an accurate answer to the problem under investigation. However, these models require computational power to provide these solutions. When a problem is highly complex in its description, the mathematical formulation of the program will also tend to be very complex. The computational power required for these formulations is often not available or the system is simply too complex to be modelled mathematically. The alternative approach in this case would be to study the problem through simulation (Law, 2015).

Simulation

Banks (1998) describes simulation as the imitation of the different operations of a real-world process or system over time. Simulation generates, through its replication of the system, an artificial history of that system. When studying this artificial history, conclusions or assumptions concerning the real-world process or system can be made. In simple terms, a simulation model can show how the variation of input data of individual processes affect the output or results of an entire system or process.

The nature of the system lends itself to different categories of simulation modelling as defined by (Law, 2015). A simulation model can be static or dynamic. In a dynamic simulation model the system evolves over time, whilst in a static simulation model, the system is shown at a particular point in time. The next categorisation is dependent on the presence of probabilistic components. A simulation that does not have any probabilistic components is called a deterministic simulation model. While the opposite, a system containing some element of randomness in inputs, is known as a stochastic simulation model. Finally, a simulation model can either be discrete or continuous. In a discrete system, the states of variables change instantly at separated points in time. The state of variables in a continuous system changes continuously with respect to time. However, Law (2015) states that it should be noted that a discrete simulation model is not always used to model a discrete system and *vice versa*. This decision is dependent on the goal of the simulation study.

Based on these characteristics there are three main simulation modelling paradigms namely discrete-event simulation (DES), agent-based modelling (ABM) and system dynamics (SD). Also worth mentioning is the Monte Carlo simulation. The Monte Carlo simulation method (MC) is a simulation model that generates random numbers in order to solve different problems (Law, 2015).

DES consists of modelling a system as it evolves over time. This is done through the representation of state variables that change instantaneously at separate points in time (Law, 2015). In DES, these points in time are referred to as events. A system and its operations can be modelled through the use of process flow diagrams, where the states of variables change at specific points in the process. DES allows for very detailed analysis of a process and is used at a low level of abstraction.

ABM is a relatively new method of simulation modelling. The word agent refers to an autonomous entity that can perceive its environment. The agent can utilize this in order to make certain decisions. ABM is an extension of DES where the agents within the model are able to interact with their environment as well as with other entities (Law, 2015). Agents can be modelled at a wide range of abstraction. As a result, ABM is extremely versatile, and can be applied to a variety of different problems.

SD is a type of continuous simulation and focusses on the entire system as a whole. System dynamic models are often deterministic, although stochastic elements can be incorporated. It is applied to very high-level or strategic problems. In system dynamics, the interactions within the model are important, but the characteristics of individual entities are not (Law, 2015).

A MC simulation is defined as a stochastic DES. It uses random number generation to solve specific problems in statistics that are applicable to real-world problems. It is a tool used to simulate the behaviour of complex systems using inferential statistics (Law, 2015).

Simulation Modelling in the Fleet Sizing Problem

Simulation modelling has been a useful solution approach to the fleet sizing problem due to the complexities often encountered in attempts to solve the problem. Lesyna (1999) applies DES to a fleet sizing problem involving rail cars. The author highlights that the use of DES enabled him to model a complex and dynamic system involving random variables, and apply the model to optimally size the rail-car fleet. In a study of the chemical supply chain, Sha and Srinivasan (2016) propose that the use of ABM is a natural fit for this industry due to its ability to describe intricate business processes. Sha and Srinivasan (2016) developed an ABM that captures the dynamics between the logistics and several other elements in the environment. This model is used to illustrate the impact of different fleet sizes on the performance of the supply chain. In addressing the fleet sizing problem for refrigerated containers, Imai and Rivera (2001) initially proposed an analytical model for situations involving both balanced and unbalanced trade. The authors then used simulation in order to extend the problem to more accurately reflect real-world conditions.

Comparison of Solution Approaches in the Fleet Sizing Problem

All of the solution approaches described in this section can be used to solve the fleet sizing problem. There are, however, certain advantages and disadvantages associated with each approach. These advantages or disadvantages dictate the degree to which the solution approach under consideration can be applied to a specific fleet sizing problem. Table 2.1 illustrates the high level differences between the different approaches.

Table 2.1: Fleet Sizing problem- Solution approach comparison

Category	**Analytical Methods**	**Optimisation Methods**	**Simulation Methods**
1. Accuracy	Provides a very accurate/ exact solution	Seeks to provide an optimal solution when an exact solution is not feasible/ possible	Seeks to provide an approximate solution, with accuracy dependent on input data
2. Scalability	For complex problems, it can be difficult to create a mathematical abstraction of the problem. Difficult to scale.	Very difficult to scale problem as complexity and variables increase	Can be used for very complex problems. Very easy to scale
3. Computational Power	As the problem complexity increases, more computational power is required	As the problem complexity increases, more computational power is required	Low computational power requirement
4. Complexity	Complex mathematical formulations	Complex mathematical formulations	No need for complex mathematical formulations
5. Practicality	Limited to problems that can be represented mathematically	Limited to problems that can be represented mathematically	Able to incorporate complex interdependencies of real-world operations

2.4 Applications of the Fleet Sizing Problem in Different Industries

The fleet sizing problem is most commonly found in businesses that are involved in the transportation of goods or services. However, it is not limited in application to only this sector. Various problems in other industries seek to answer the basic questions addressed by the fleet sizing problem (Shyshou et al., 2009).

Given the small economic margins in the road freight industry and the costs associated with operating big vehicle fleets, the fleet sizing problem is especially important in this industry. Zak et al. (2008) describe a fleet sizing problem in the context of a road freight transportation company, operating a heterogeneous fleet. Similarly, Wu et al. (2005) address a problem in the truck-rental industry. While considering the demand and the allowed level of stock outs, Du and Hall (1997) seek to determine the minimum fleet size in a transportation service utilising trucks.

In transportation, Ceder and Stern (1981) describe a problem where the size of the bus fleet of an Israeli bus carrier needs to be determined. Song et al. (2007) aim to optimise the vehicle fleet size of a shuttle service where vehicles move between terminals in order to pick up customers at random points in time.

The fleet sizing problem is also found within the manufacturing industry. Hall et al. (2001) consider the problem of determining the minimum number of AGVs required for material handling in a flow shop layout. Turnquist and Jordan (1986) examine the required fleet size for the shipment of parts from a manufacturing plant to different assembly plants where, amongst other factors, the part production cycle is considered.

In a study initiated by a Norwegian oil and gas operator and conducted by Shyshou et al. (2009), the focus is on the anchor handling operations associated with the movement of offshore drilling rigs. Rig movements are performed by tug supply vessels. The study considers the strategic decision of determining the fleet size of these tug supply vessels. The fleet sizing problem has interesting applications in the maritime environment. Pantuso et al. (2014) present a survey on some of these problems.

In rail, freight cars represent a major capital investment. A natural objective is to determine the optimal freight car fleet size. In separate studies, both Bojovic (2002) and Sayarshad and Ghoseiri (2009) propose a procedure for determining the optimal fleet size for a fleet of rail-cars.

Vis et al. (2005) describe a problem encountered at a container terminal. During the loading and unloading of containers from container ships, the container needs to be transported from a buffer area to the transport vehicle. This movement is done with specialised vehicles like straddle carriers or Automated Guided Vehicles (AGVs). The objective of this study is to minimise the fleet size of the vehicles moving the containers in the terminal, whilst ensuring that all the required container movements are completed timeously and the buffer area's capacity is not exceeded.

The application areas described in this section is by no means an exhaustive list. However, it does illustrate the versatility and value of the fleet sizing problem in various industries.

2.5 Chapter Summary

This chapter is dedicated to a review of the academic literature related to the fleet sizing problem. The concepts discussed are central to the approach adopted toward addressing the problem considered in this project. The chapter opens in §2.1 with an overview of the fleet sizing problem. In §2.2 the reader is provided with the different ways to classify the fleet sizing problem. This is followed by §2.3 where the reader is provided with some insight into how practitioners have gone about solving the fleet sizing problem. The chapter comes to a close in §2.4, where some of the different applications of the fleet sizing problem is highlighted.

3 Research Methodology

Chapter 3 describes the research methodology that will be followed in the pursuit of developing a solution to the problem described in chapter 1. This chapter opens in §3.1, where the research design for this project is described. Then in §3.2, the methodology that will be followed for the execution of this project is provided.

3.1 Research Design

Upon examining the literature on the fleet sizing problem in Chapter 2 and after considering the problem formulated in §1.2, it was concluded that a simulation model will be used to answer the research question of this project.

The problem described in §1.2 is very complex. It involves describing the numerous tractor services (Appendix B) required to support production activities. Each of these activities are dynamic and their demands contain certain elements of uncertainty. Apart from these services, the environment, the downtimes and maintenance of tractors, travelling times and other factors are to be incorporated in the model, resulting in numerous variables and interactions that need to be considered.

The real-world system for this problem is too wide and complex to permit a mathematical representation of the problem and therefore it is not possible to derive a solution mathematically or through the use of optimisation techniques. Simulation is used when experimentation with the real system may be impractical, impossible or simply too expensive (Law, 2015).

A simulation model is to be used in order to provide valuable information on the tractor services and the environment in which they operate. This model will be utilised in order to perform experiments through the variation of certain parameters or variables. In the analysis of the results from these experiments, a recommendation regarding the tractor fleet size can be made.

3.2 Methodology

This section describes the simulation modelling methodology that will be employed for this project. In the *Handbook of Simulation* edited by Banks (1998), a systematic step-by-step approach in the design and development of a simulation study is suggested. A depiction of the steps can be found in Figure 3.1 below. These steps will be followed for the execution of this project. A detailed explanation of each step and how it is to be applied in the context of this project is provided.

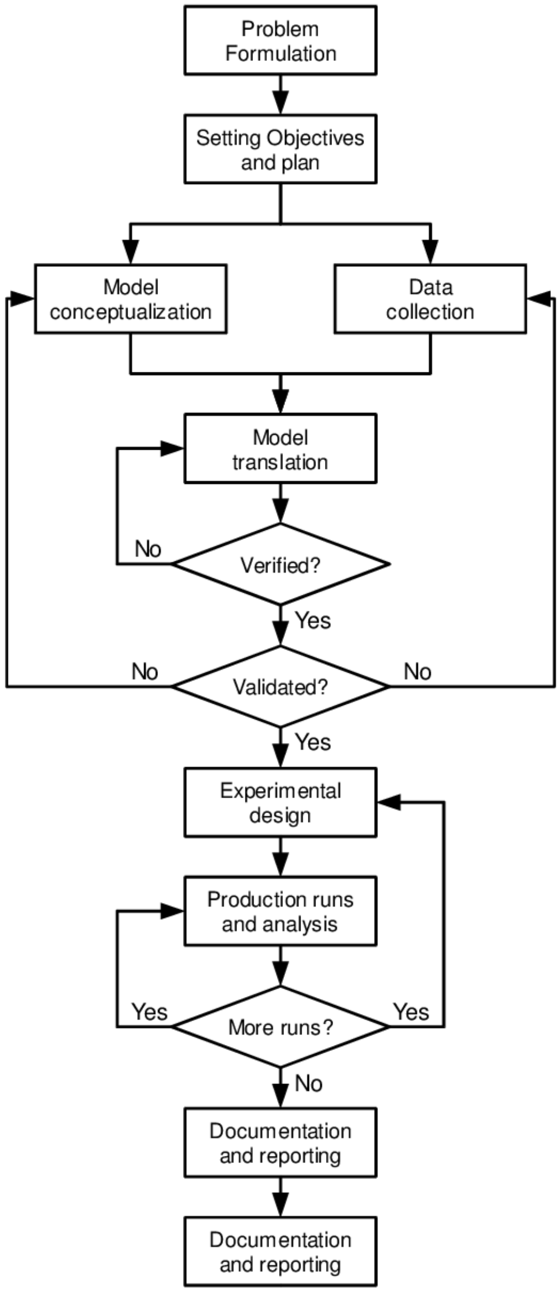

Figure 3.1: Steps in a simulation study as adapted from Banks (1998)

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1. **Problem formulation**

   The first step in any project is understanding the problem. A simulation study is no different. This step involves engaging with the various stakeholders at Sasol Mining. The problem formulation is critical in defining the boundaries and scope of the project due to the size of the operating environment. Once the problem is fully understood, a clear and concise problem statement can be developed. The problem formulation in this project is provided in §1.2.

2. **Setting objectives and plan**
   Once the problem has been clearly defined, the objectives and overall project plan can be developed. Section 1.3 builds on the problem statement and provides the research question and objectives of this project. The research question and objectives indicate the aim of this simulation study. The project plan is based on the methodology described in this chapter and can be found in Gantt-chart form in Appendix A.

3. **Model conceptualisation**
   Banks (1998) proposes that a simple, initial model is formulated. This model shown in Figure 3.2 is used to gain a deeper understanding of the production support services that utilise tractors and the environment in which they operate.

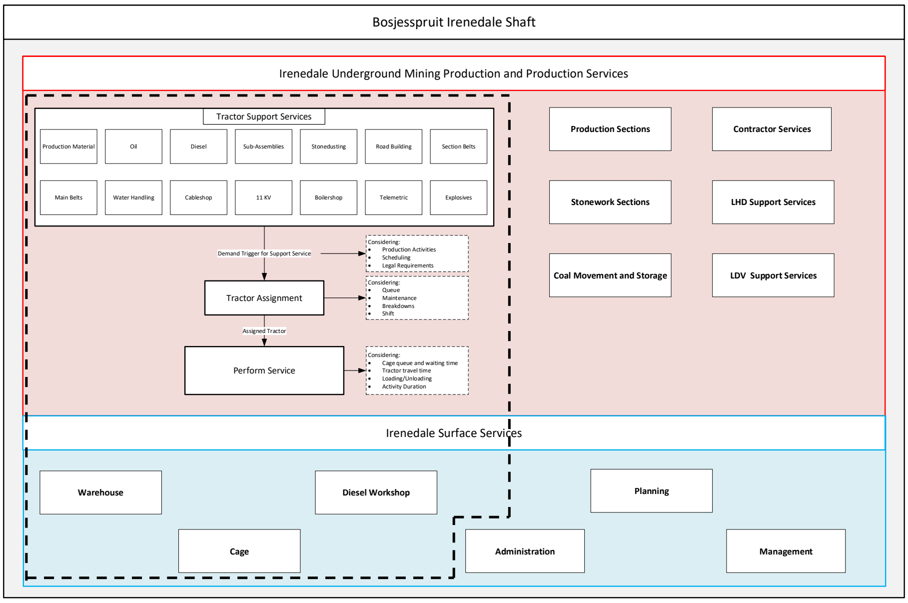

Figure 3.2: Project Conceptual Model

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From conceptual model the system boundary can be reduced to the underground tractor support services at the Bosjesspruit mine as well as some service activities that influence the tractor fleet operations.

The system boundary is indicated on the conceptual model by the dotted line in Figure 3.2.

The scope of the project will be limited to the production support services provided by flame-proof tractors along with certain areas that affect their operations.

Due to the complexity associated with the problem described in §1.2, the scope of the project will be limited by the following general assumptions:

Surface operations and activities. All surface activities are excluded from this project. The only exception are areas that form part of or impact the tractor services. These include the warehouse, diesel workshop and the cage (used for the transportation of people and equipment from the surface to underground).

Production and stonework activities. Mining operations at each of the production and stonework sections are not explicitly considered. The aim of the support services is to enable production. This means that only the service requirements stemming from production and the rate at which these services are needed are of importance.

Support services. For the purpose of this study, only flame-proof tractors and the services provided by it as described in Appendix B are considered. Any other equipment used in support of production is not of importance in this project. This includes the services provided by load haul dump (LHD) loaders, light duty vehicles (LDVs), graders, front end loaders as well as non flame-proof tractors and any other machines used at the mine.

Contractor equipment. Whenever a service is rendered by an external contractor, both the service and the tractor requirements are excluded from this project.

Trailers. In order to reduce the complexity of the project, trailers are not explicitly considered. It is assumed that whenever a tractor requires a trailer for the completion of a service, the correct trailer will be available for use.

Travel times. The assumption is made that all flame-proof tractors are homogenous, and that their travel times are dependent only on the distance travelled between underground locations and the average speed of the tractor.

Assumptions pertaining to each of the individual services and components will be clarified in the subsequent chapters.Table 3.1 below describes what will be included and excluded within the scope of this project.

Table 3.1: Project scope

Included in Scope	**Excluded from Scope**
Tractor support services. Full list in Appendix B	Production Section Activities (Mining)
Diesel Workshop	Stonework Production Sections
Material Winder (Cage)	Contractor Services
Warehouse	LHD Production Support Services
Travel times	LDV services
Breakdown and Maintenance	Coal Movement and Storage
	Trailers
	Surface Operations (excluding the cage, warehouse and diesel workshop)
	Planning
	Management

4. **Data collection**

   In this step, the input data for the model is collected. For this project various types of data from a number of different sources are required. In this project both quantitative and qualitative data collection methods are used.

   Input data on the demand for the respective production support services is required. This will be collected through various methods. Quantitatively, historical data, schedules or legal requirements will be collected. The data originates in a multitude of locations. These include *Excel* spreadsheets, the *SAP* ERP system and various others. Where quantitative data is not available or sufficient, qualitative data in the form of semi-structured interviews with subject matter experts at the mine will be collected.

A summary of some of the data requirements as well as the collection plan for these is provided in Table 3.2. The time frame for data collection is provided in the project timeline in Appendix A.

Table 3.2: Data collection

Data Requirement	**Data Collection Plan**
Travelling road distances	Mine planning data
Underground locations of facilities and mining areas	Mine planning data
Tractor availability	Downtime and breakdown bookings recorded on *SAP*
Production mining rate	Mine production data
Production material consumption rate	Production material requirement based on mining activities
Oil consumption rate	Historic data
Sub assembly deliveries	Historic data
Diesel consumption rate	Consultation with mine manager
Stonedusting requirements	Consultation with mine manager
Road building requirements	Consultation with mine manager

Once the various data has been collected, it will be analysed using an applicable tool like *Excel* or *Minitab*. The type of analysis employed depends on the purpose for which the data is used.

5. **Model translation**

   The conceptual model developed in step 3 is programmed into a simulation software program. The *AnyLogic* simulation modelling tool developed by the *AnyLogic Company* will be used in this project. AnyLogic uses Java and object-oriented programming methods. It allows modellers to use all three modelling paradigms. DES, ABM and SD can be used separately or in combination.This provides the modeller with a lot of freedom when translating the conceptual model into an executable simulation model in order to gain insight into complex systems and processes.

6. **Verification**

   Verification is concerned with the operational model. Its purpose is to ensure that the model is functioning as it should (that is, does the model logic and input data yield sensible results). Verification is a continuous process that should be done throughout the modelling process (Banks, 1998).

   The process of verification therefore involves continuous debugging throughout model development to ensure that the model constantly functions correctly.

   In this project verification will be aided by the AnyLogic software. First, syntax errors are quickly identified and highlighted. Secondly, AnyLogic places some emphasis on animation. Animation is excellent for model verification as results can be easily verified through observing the model and monitoring the movements of entities within the model.

   Additional verification will include stress testing of the simulation model through extreme parameter variation, as well as reducing stochastic variables to deterministic variables. The change of stochastic to deterministic allows the modeller to exclude stochastic variability when comparing model output.

7. **Validation**

   Validation seeks to determine whether the simulation model is an accurate representation of the real-world system it seeks to emulate. The purpose of validation is to ensure that the model is an accurate substitution for the real system for the purposes of experimentation (Banks, 1998).

   Validation of the simulation model in this project will be done in two ways. Firstly through parameter variation. Parameter variation is done through varying user-determined input values and evaluating the model outcomes.

   Secondly, and according to Banks (1998) the ideal way of model validation, model output should be compared against a current scenario. The first simulation model will be based on the current scenario at the Bosjesspruit mine. The output of this model will be compared against current operations through the analysis of historic data and by consulting with subject matter experts at the mine. This comparison ensures that the model is an accurate representation of the production support services at the mine, and that the model can be used to simulate different scenarios to a high degree of accuracy.

8. **Experimental design**

   Experimentation with the simulation model allows the modeller to test different scenarios or to solve the identified problem.

   The scenario to be simulated in this project is to modify the shift system of the model and the number of production sections to reflect the implementation of the Fulco shift system at the mine. The experiment will run over a period of several months in order to ensure that the full spectrum of events can be simulated.

9. **Production runs and analysis**

   After production runs are completed, an analysis of the output data from the simulation model is required. The results of this analysis are used to estimate measures of performance for the scenarios that are being simulated (Banks, 1998).

   The analysis of this project will look at a number of variables used to make a decision regarding the tractor fleet size. These include the utilisation of tractors as well as the number of stock out occurrences or instances where a service could not be completed within the simulated period.

10. **More runs**

    After the initial production runs and analysis, it might be required to perform further runs. This can be to test different scenarios or for further analysis of existing scenarios.

11. **Documentation and reporting**

    Banks (1998) emphasises the importance of documentation, stressing that detailed and thorough documentation is critical if the model will be used again or by different analysts. This project is no different. Documentation will be provided to ensure that Sasol Mining is able to use the model in future and at different mines.

3.3 Chapter Summary

This chapter highlights the research approach chosen to address the problem described in §1.2. The chapter opens in §3.1 with an explanation as to why the problem described in §1.2 and studied in Chapter 2 can be approached through the use of simulation modelling. In §3.2 a well known methodology used to approach simulation modelling problems is detailed. The remaining chapters in this report seek to expand on the steps suggested by Banks (1998) and described in this chapter.

4 Model Development

Chapter 4 describes the development of a simulation model of the tractor services at the Bosjesspruit mine. The chapter opens in §4.1 with a description of the tractor services and their respective processes included within the scope of this project. The data requirements, collection and analysis for both the services and important components within their operating environment are provided in §4.2. This section also describes any assumptions made with regard to a particular support service. A brief introduction to the *AnyLogic* modelling software is given in §4.3, before describing the model translation into the *AnyLogic* modelling software.

4.1 Tractor Support Services

This section provides the reader with background information on the different tractor support services and the functions that they fulfil within the mine.

4.1.1 Logistics

The logistics department serves three main functions: to provide production sections with production material, to facilitate oil deliveries and to ensure the availability of diesel.

Production Material Deliveries

Production material consists of roof bolts, roof bolt resin and cutting picks. The roof bolts and resin is consumed by the roof bolter in order to provide secondary roof support, whilst the cutting picks are used by the continuos miner to enable the efficient cutting of coal at the working face. The consumption of this material is dictated by the production rate and ground conditions of the production section. The delivery process at the Bosjesspruit mine is shown in Figure 4.1.

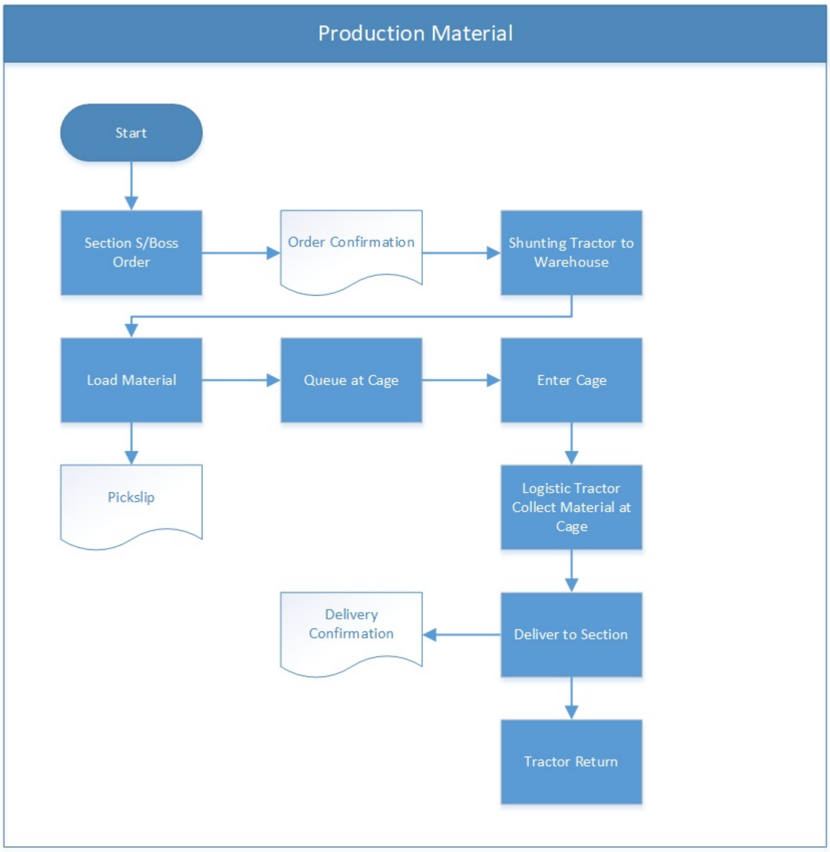

Figure 4.1: Production material delivery process

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Oil Distribution

The second function is to provide oil to production sections. The mine uses two types of oil in its daily operations. These differ in function and frequency of use. However, the process of delivering both of these is identical. This is shown in the process flow diagram depicted in Figure 4.2.

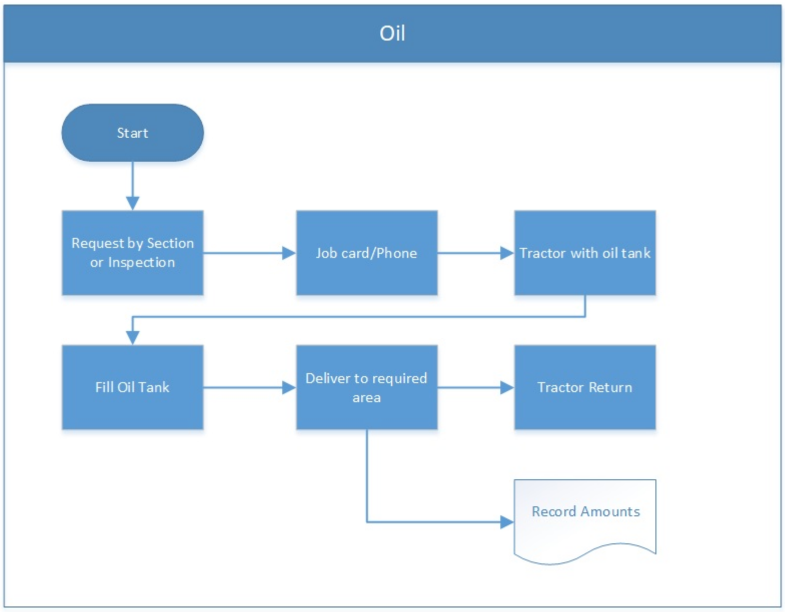

Figure 4.2: Oil delivery process

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Diesel Distribution

The last role of the logistics department is to ensure the availability of diesel in the form of diesel bowers located strategically throughout the mine. Figure 4.3 illustrates how the task of refilling the diesel bowsers is completed. Diesel is consumed by vehicles like LDVs, LHDs and tractors.

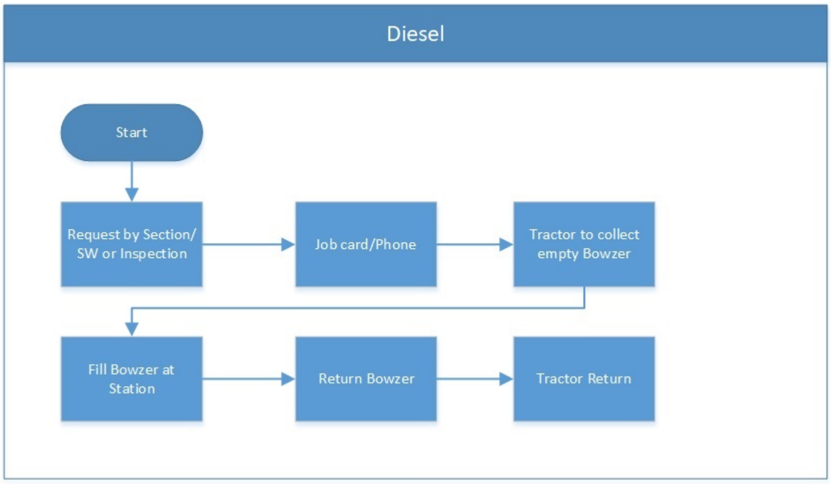

Figure 4.3: Diesel bowser refilling process

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4.1.2 Road Building

As mining activities occur at the different production sections, the mine expands. This expansion requires that the road network be continuously maintained in order to facilitate movement of employees, machines and materials underground. The road building operations consist of graders creating and repairing new or existing roads. The role of the tractors is to provide gravel and water to the process, as depicted in the process flow diagram shown in Figure 4.4.

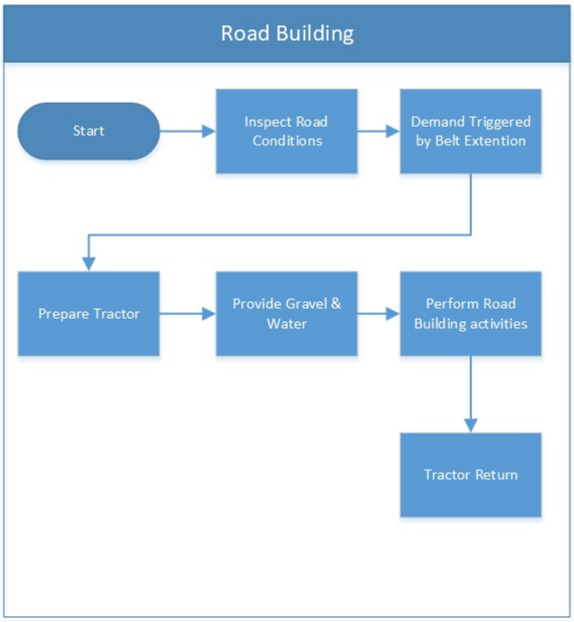

Figure 4.4: Road building process

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4.1.3 Stone dusting

Stone dusting is a requirement within underground coal mines. It involves the application of stone dust along mine roadways and working faces. The purpose of stone dusting is to cover coal dust and reduce its flammability. This will ensure that in the event of an explosion, the effects are less violent. Stone dust can be applied in several different ways, although it is common to make use of automated stone dusters. Figure 4.5 provides an example of a tractor towing a stone dust trailer, applying stone dust in a roadway.

Figure 4.5: Stone dust applied to a roadway

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Stone dusting at the Bosjesspruit mine makes use of tractors to tow automated stone dust trailers that apply stone dust to the required areas in the mine. A simple process flow diagram, shown in Figure 4.6 illustrates this process at a high level.

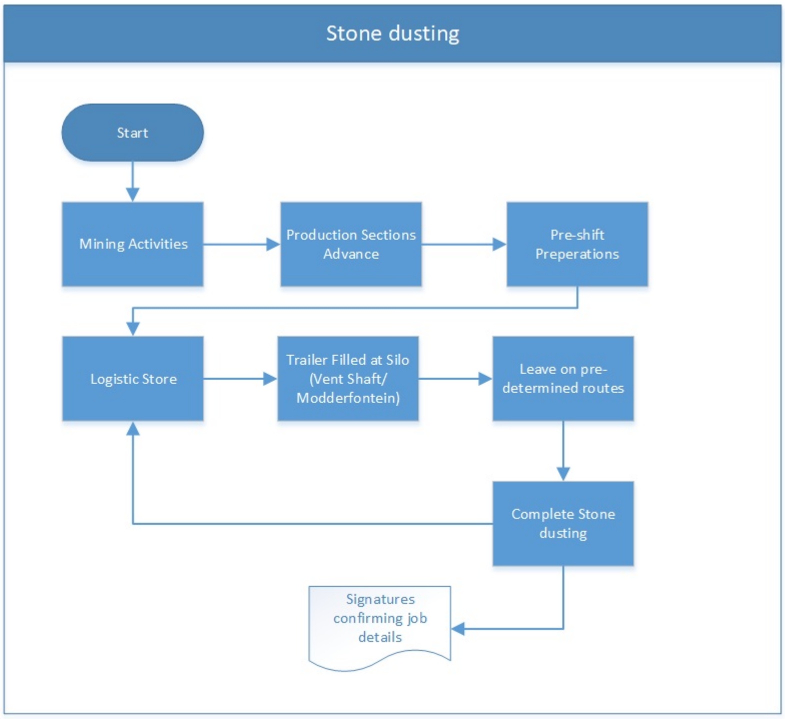

Figure 4.6: Stone dusting process

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4.1.4 Sub-assembly Deliveries

A sub-assembly is a machine or equipment part that forms part of a larger assembly. Sub-assemblies are required to repair or maintain the equipment or machinery used for the different operations underground. The delivery of larger sub-assemblies are facilitated by tractors at the Bosjesspruit mine, again Figure 4.7 illustrates this process at a high level.

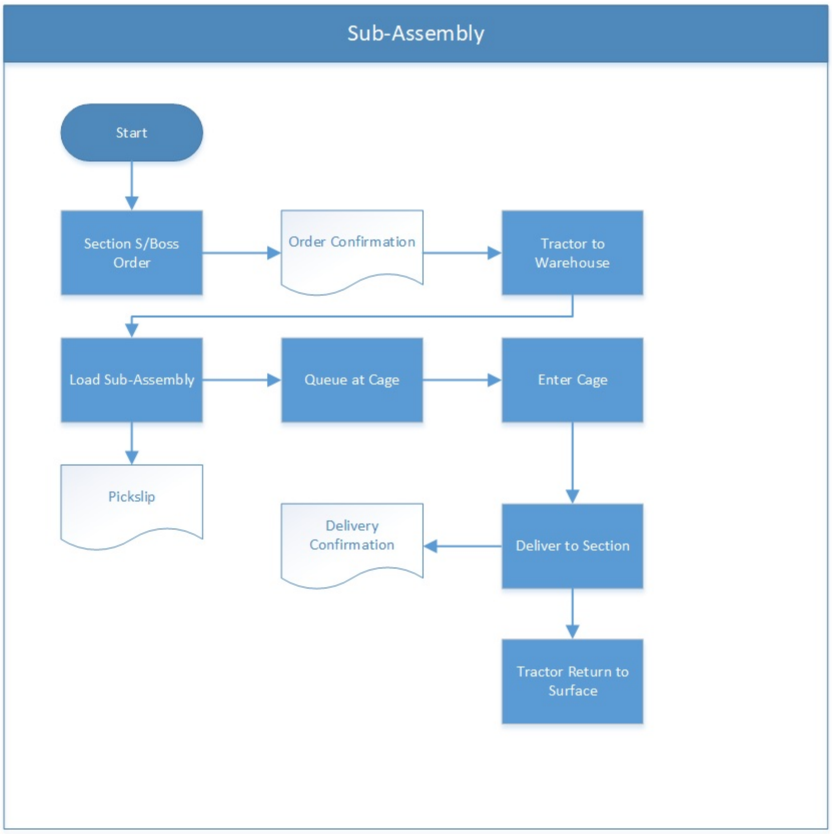

Figure 4.7: Sub-assembly delivery process

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4.2 Data Collection and Analysis

Step four in the design and development of a simulation, as described in the previous chapter, involves data collection. This section highlights the data collection and data analysis process for various different services and components within the mine. Additionally, insight is given into the assumptions made in order to simplify the processes to an appropriate level of granularity.

4.2.1 General Information on the Bosjesspruit Mine

In order to model tractor operations at the Bosjesspruit mine, Irenedale shaft, some general information is required. The mine consists of nine production sections (before the implementation of the Fulco operations). Combined these sections are responsible for total coal production at the mine. The room and pillar method is utilised, as described in §1.1.1.

The locations and distances between production sections is shown in Appendix C. These locations and distances are used in the modelling of tractor movement in the mine. Even though the mine is constantly expanding, the assumption is made that the rate of expansion is gradual enough for the underground layout to remain fixed for the simulation period.

For the purpose of this project, the specific mining activities that occur within the production sections will not explicitly be considered. Rather, the effect of these activities will be shown simply through the effect that coal production has on the various tractor support services.

In order to show this effect, the historic production data per section per shift for a period of 22 months will be used as a variable input. After cleaning the data set and removing zero values, the data set size consists of 8358 entries. A distribution fitting in the *Minitab* statical software version 20.1.3 resulted in a 3-Parameter Weibull distribution fitting, shown in general form in equation 4.1 below.

$$f(t) = \frac{\beta}{\eta} \cdot \left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \tag{4.1}$$

Here, β denotes the shape parameter, η the scale parameter and γ the location parameter.

This distribution will be used to simulate the mining activities on a per shift basis for each of the different production sections.

The aforementioned distribution, with parameters (2.062; 1181; 0.5752) is depicted in Figure 4.8. The zero values (representing shifts where no production occurred) are not included within the distribution. They will be incorporated as a percentage within the model.

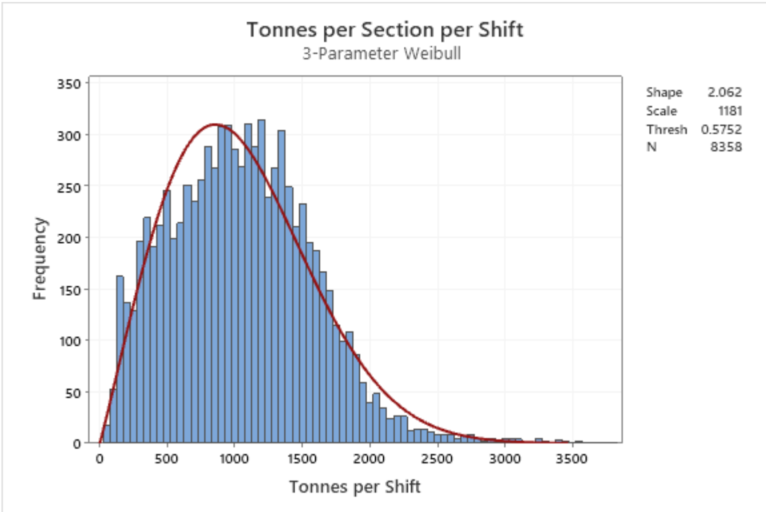

Figure 4.8: Production tonnes per section per shift

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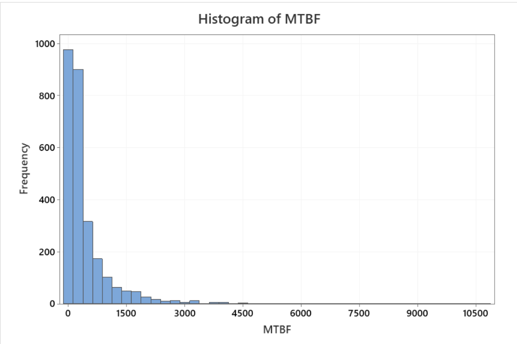
4.2.2 Tractor Fleet

As stated in §3.2, the assumption is made that all flame-proof tractors are homogenous. Based on this assumption, the availability of the tractor fleet is determined by the historic breakdowns and subsequent downtimes. Historic data is collected on the *SAP* ERP system. In order to ensure that a wide spectrum of possible failures is considered, data for 32 tractors over the period of 2014-2020 is used to calculate two metrics. These are the mean time between failures (MTBF) and the mean time to repair (MTTR).

The mean time between failures (MTBF) is the average time between breakdowns. The data per tractor was cleaned in order to remove duplicates, incorrect entries and non-relevant entries. The MTBF was calculated based on the hours between breakdown bookings. For the period under consideration, there was a total of 2741 breakdowns at an average of 85.67 breakdowns per tractor. The MTBF is 437.797 hours.

MTTR (mean time to recovery or mean time to restore) is the average time it takes to recover from a breakdown or failure. Data per tractor was cleaned to remove duplicates, incorrect entries and non-relevant entries. Downtimes also had to be grouped in order to ensure that the total downtime for a particular breakdown is captured. The MTTR was calculated based on the total downtime booked per individual breakdown. For the period under consideration, the MTTR is 41.93 hours.

In order to introduce variability into the model, the MTBF and MTTR will not be introduced as averages. The *Minitab* software determined that both data sets do not follow any theoretical distribution. However, the datasets are large enough to enable random sampling within the sets. This sampling is based on the probability of occurrence and facilitated within the *AnyLogic* modelling software. The MTBF and MTTR data is shown in Figure 4.9.



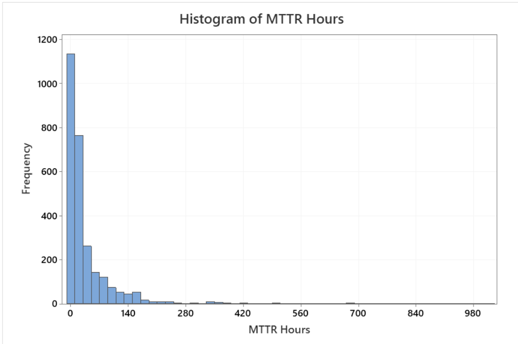


Figure 4.9: MTBF and MTTR data for the Bosjesspruit tractor fleet

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Dependent on the type of breakdown and the availability of resources, a breakdown can either be repaired underground or at the diesel workshop. If it is repaired at the workshop, the tractor needs to be taken from the mine to the workshop on surface. However, no distinction is made in terms of the downtime booking, thus the assumption is that all breakdowns are repaired underground as the MTTR includes both the towing and waiting time.

Another factor to consider is the scheduled maintenance of equipment. At the Bosjesspruit mine there are two types of scheduled maintenance, namely two-weekly maintenance that is completed underground and eight-weekly maintenance that requires that the tractor be brought to the diesel workshop located on surface.

4.2.3 Cage

A cage is raised and lowered by a winder engine, and is a very important component for any underground mining operation. It is analogous to a service elevator and used to transport workers, equipment and machines vertically from the surface to underground and *vice versa*.

The Bosjesspruit main cage is used for the transportation of workers, as well as any equipment that needs to move from the surface to underground or from underground to surface. It is an important aspect of the tractor support services considered in this project as both production material and subassembly deliveries require the use of the cage. Additionally, the scheduled eight-weekly maintenance requires the tractor to use the cage *en route* to the diesel workshop.

The cage is used by all the equipment on the mine. This high demand and limited capacity (only one machine is permitted inside the cage), results in waiting time for tractors in need of the cage. To incorporate this delay into the model, the cage has to be included.

The cage is used by both workers and machines. However, its use is determined by a schedule. For workers the cage is available at the start and end of a shift, whilst machines are transported in between these times. The cage is also unavailable during the scheduled weekly maintenance.

This project is limited to tractors, thus there is a need to represent the occupancy of the cage by other machines. A dummy arrival rate functions as a queue representing machines other than tractors utilising the cage in the daily operations of the mine. This dummy arrival rate is calculated by considering the average number of daily trips made by the cage over the period of 2015-2020, then deducting the number of trips dedicated to tractors and workers. Thus, dummy trips are equal to 23 per day. To introduce variability, a triangular distribution with parameters (21, 25, 23), will be used to allow for 10% deviation from the average.

4.2.4 Logistics

As described in §4.1.1, the logistics department serves three main functions: to provide production sections with production material, to facilitate oil deliveries and to ensure the availability of diesel.

Production Material Deliveries

As production occurs at the different production sections, these sections advance forward. This advance triggers the need for production material by the section in order to provide roof support in the newly mined areas. The section advance or linear advance is based on the tonnes mined during a shift, the width of the roadway, the height of the coal seam and the relative density of the coal. It is calculated by the following equation,

$$\text{Section Advance} = \frac{\frac{Tonnes}{RD}}{W \times H},$$

where RD $= 1.5\frac{Tonnes}{m^3}$ represents the relative density of the coal seam, whilst W $= 7.2m$ and H $= 3m$ represent the road width and seam height respectively. All three values are treated as constant throughout the Bosjesspruit mine. This means that the tonnes produced by a production section, derived from the distribution shown in Figure 4.8 determines the section advance during a shift.

The need for roof bolts are the determining factor in a production material delivery, thus to calculate the production material delivery frequency, it is important to consider the amount of roof bolts required.

This calculation is based on the following equation,

$$\text{Roofbolts required} = \text{Bolts per } m^2 \times \text{W} \times \text{Section Advance}$$

where the Bolts per m^2 is defined by,

$$\text{Bolts per } m^2 = \frac{\text{Bolts per row}}{\text{W} \times \text{Spacing Between Rows}}.$$

The Bolts per m^2 is assumed to be a constant as the Bolts per row $= 5$, and the Spacing Between Rows $= 2m$. This means the number of roof bolts is determined by the number of meters a section advances, which is determined by the production in that shift. The system employed at the Bosjesspruit mine requires that a production material delivery occurs in batch sizes of 1000 roof bolts (combined with the complimentary resin and cutting picks). This means that when a production section has mined a sufficient amount of tonnes (to use 1000 roof bolts), a production material delivery is required.

Oil Distribution

In order to determine the oil delivery interval, historic delivery data was collected. The period for which reliable information was available is for 11 months. This data set contains 273 deliveries and resulted in a delivery interval that can be represented with a 3-Parameter Gamma distribution, shown in general form in equation 4.2 below,

$$f(x) = \frac{1}{\tau(k)b^k} \cdot x^{k-1} e^{\frac{-x}{b}}. \tag{4.2}$$

This distribution, with parameter values of (2.075; 6.316;0.3703), indicates the number of shifts between oil deliveries to each of the production sections and is shown in Figure 4.10.

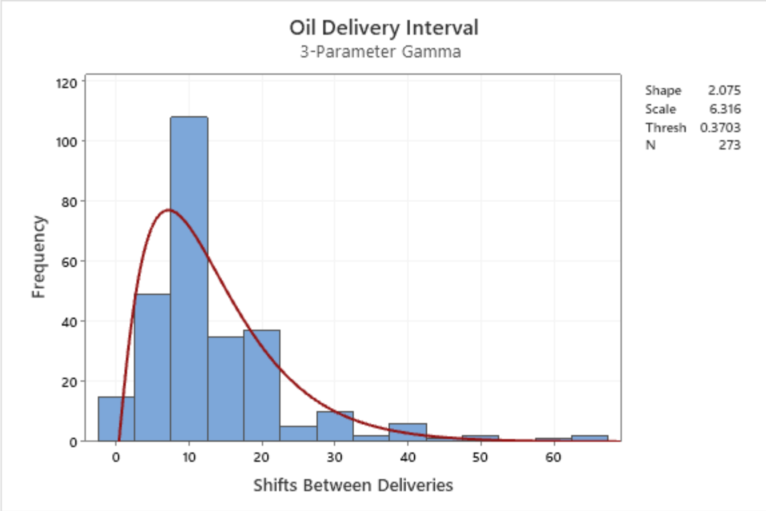

Figure 4.10: Oil delivery interval

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Diesel Distribution

The role of the tractor fleet with regard to diesel consumption is limited to ensuring that the diesel bowsers are refilled when required. At the Bosjesspruit mine these bowsers are not used frequently as operators prefer to utilise the main diesel bay underground. This means that the process of refilling these bowsers is infrequent and on an *ad-hoc* basis. Upon consulting subject matter experts, the diesel deliveries will be represented by a triangular distribution based on qualitative estimates combined with observed data. Within the model, diesel deliveries will be represented by a triangular distribution with parameters (1,2,4). This indicates the number of deliveries per week.

4.2.5 Road Building

Road building is primarily done in sections where mining and support activities have progressed up to the point of a belt-extension. A belt-extension is the process of moving the production section forward when they have advanced a certain number of meters. This serves as the trigger for the road building team. At the Bosjesspruit mine, a belt-extension occurs every 56m. This means that when the section has advanced 56m forward, there will be a belt-extension. Within the simulation model, the demand for road building is triggered once the section advance (determined by the tonnes mined) reaches 56m.

Apart from the road building activities due to belt-extensions, the road building department is also responsible for dust-suppression. Dust-suppression is done according to a schedule, where a tractor is responsible for applying a chemical on the roads throughout the mine in order to reduce the presence of dust in the mine.

4.2.6 Stone dusting

As mentioned in §4.1.3, regular stone dusting is not only a legal requirement, but also a critical safety feature in any underground mine. As such, a lot of emphasise is placed on the stone dusting activities at the Bosjesspruit mine. The stone dusting activities can be divided into two areas. The first, and most important is in the production sections whereby mining activities necessitate the need for stone dusting. The second is in non-production areas throughout the mine. Both of these are addressed via predetermined routes that operate on a schedule to ensure that all areas are addressed. The stone dusting schedule attends to production areas during the maintenance shift every night, whilst secondary areas are attending to during the day shift or over weekends in order to limit the affect on production activities. Within the model, both the routes and the schedule will be used as a direct input in order to simulate the stone dusting process.

4.2.7 Sub-assembly Deliveries

Sub-assemblies are delivered to the sections with the use of tractors that are stationed on surface. These sub-assemblies are delivered on an *ad-hoc* basis, mostly triggered by breakdowns. Historic data for the period from 2017-2020 for both planned and breakdown sub-assembly requests per day was analysed in order to determine a demand pattern. The data set consists of 1310 entries, shown in Figure 4.11.

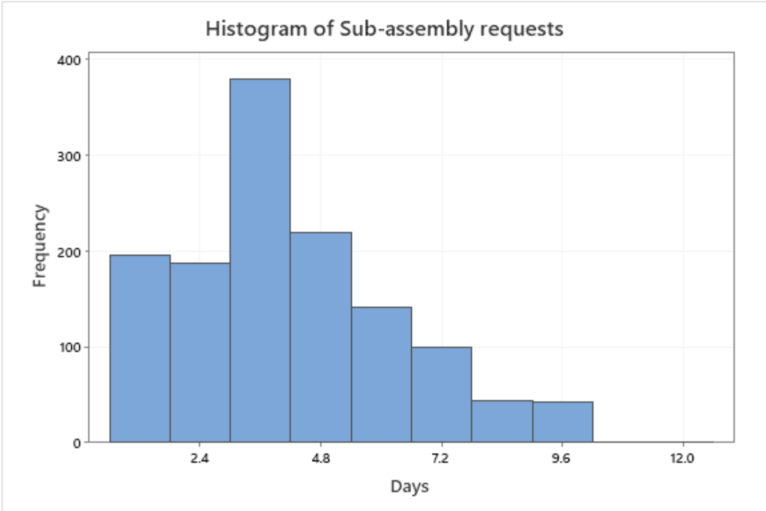

Figure 4.11: Sub-assembly request data

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Due to the nature of these deliveries, (often unplanned due to unforeseen equipment breakdowns), there is no theoretical distribution that can accurately describe the behaviour of the data set. Similar to the MTBF and MTTR described earlier, the dataset is large enough to enable random sampling within the set. This sampling is based on the probability of occurrence and facilitated within the *AnyLogic* modelling software.

4.3 Model Translation

The *AnyLogic* Professional Edition 8.7.4 software suite is used in order to model the Bosjesspruit mine and the various tractor support services that are described in this chapter. *AnyLogic* allows the modeller to make use of all three simulation modelling paradigms: Discrete-Event, Agent-Based and System Dynamics can be used separately or in conjunction within the *AnyLogic* software. In order to model the operations at the appropriate level of granularity, a simulation step interval of one hour is incorporated into the simulation settings. Within the software different components are used to define agents, variables and schedules amongst others. In this section, some of these symbols are provided for illustrative purposes when describing the model translation in the *AnyLogic* software.

To incorporate the size and distances of the travelling roads and locations of the production sections at the Bosjesspruit mine, the mine plan shown in Appendix C is imported into the *AnyLogic* software. The plan is drawn to scale, thus the travelling roads and locations of production sections can then be super imposed on the plan. This results in a very accurate representation of the mine. This is shown in the screenshot from the model in Figure 4.12 below.

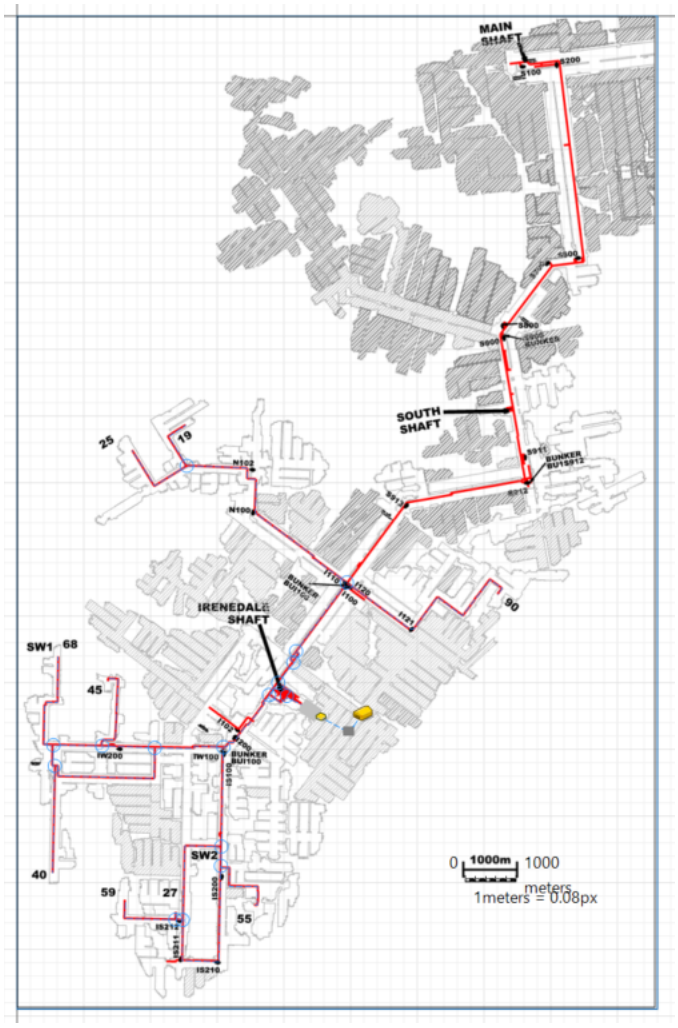

Figure 4.12: Bosjesspruit mine plan shown in *AnyLogic*

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The production shifts are built into the model with the help of schedules based on the current operation. These production shifts can either be a zero shift or a coal producing shift. This is determined based on the probability of having a shift where no coal is produced. If the shift is non-zero, the production is determined through a random sample of the 3-Parameter

Weibull distribution shown in Figure 4.8, representing the production tonnes per section per shift. This production dictates the demand for those service that are dependent of the rate of mining activities.

Each production section and tractor support service is modelled as an *Agent* . An agent can represent various elements in a model including people, equipment and organizations. The advantage of using agents in the model is attributed to the high level of flexibility it allows. Agents can have specific behaviour, memory and importantly, they are able to communicate. This communication is what drives the triggers for demand of the different tractor services from the production sections. When a production section has had a number of production shifts and their cumulative section advance necessitates a production material delivery or a belt extension, this trigger is communicated to the *OrderProductionMaterial* or the *RoadBuilding* agents. Similarly, if the oil delivery interval triggers an oil delivery, this is communicated to the *OrderOil* agent.

As mentioned, not all support services have a dynamic demand trigger. Diesel deliveries are based on a weekly rate, whilst sub-assembly deliveries are based on a daily rate calculated from historic data. The *Source* block is used to specify this arrival rate. Stone dusting is determined by a daily schedule. This constant demand is incorporated as a fixed value within the *Schedule* element in the model.

The tractor fleet is responsible for executing the services once a demand has been triggered. In order to represent resources that have limited capacity, such as tractors and the cage, the *ResourcePool* block is used. This allows various variables to be specified, such as the average speed, maintenance, failures and capacity. The screenshot in Figure 4.13 shows some of these decisions with regard to the resource pool representing the tractor fleet. The average speed is a fixed value that is based on operating specifications. The behaviour associated with maintenance and failures are controlled by the *Downtime* element. This element specifies the timing and process associated with both maintenance and failures. In terms of maintenance, the two-weekly and eight-weekly routine maintenance is included through the prescribed interval. The *CustomDistribution* element enables both the MTBF and MTTR data described in §4.2.2 to be treated as an empirical distribution. Failures, or downtimes and the subsequent repair time is determined through random sampling from these distributions. The capacity of each tractor support service is determined by the *Schedule* element, this element allows both the work schedule and the size of the fleet to be specified.

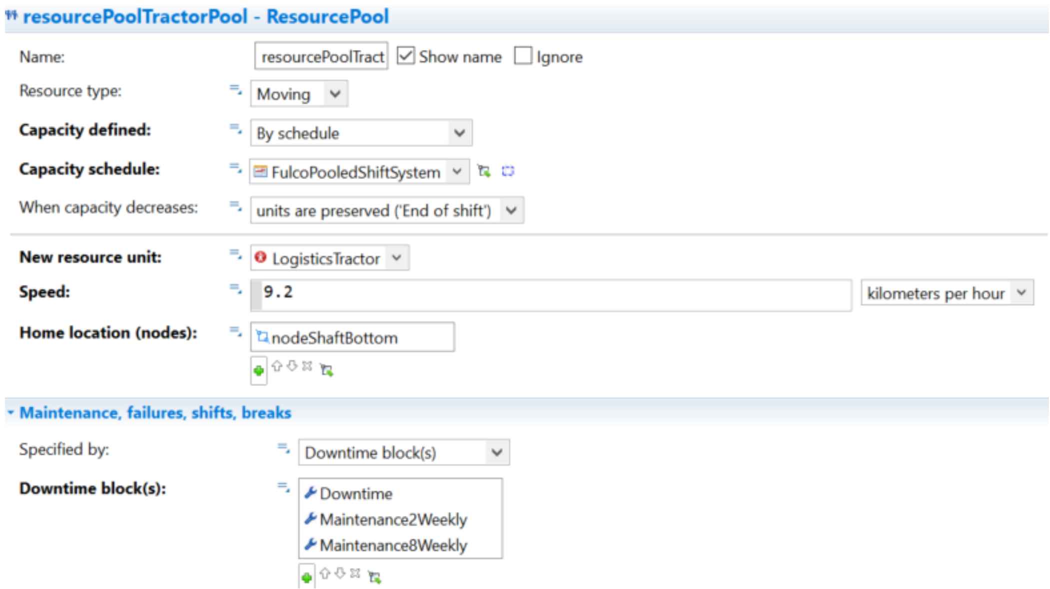

Figure 4.13: Tractor resource pool

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The individual activities associated with each of the support services are modelled as discrete-events within the *AnyLogic* software. This allows a greater level of detail to be included in each process. A number of standard process blocks are used in order to model the individual activities within each process. Some of the important element are briefly described. The *Seize* block seizes a tractor for a particular task. The *Seize* block is also used to control the usage of the cage. The *Seize* block automatically maintains a queue once no resources are available to seize. Once a resource is seized the *MoveTo* block is utilised if the resource is required to move to a different location. This movement is limited to the paths imposed on the Bosjesspruit map as described earlier.

Another important element is the *Delay* block. This delays any subsequent activity or progress until the specified delay time has been served. This is used to represent activities such as loading or unloading and the values based on operator estimates and observations. Once an activity has been completed, a tractor becomes available. Similarly, if the cage reaches the surface/underground it is also available for another piece of equipment. The *Release* block indicates that the resource is no longer in use and available for use. The complete process for each of the support services is shown in Appendix D.

When the model is run, information is collected. With the *ExcelFile* element, *AnyLogic* allows data to be written to a specified Excel file as soon as it is created. The data collected in this model is of two types. The first is summary data. This contains statistics and figures determined at the end of each simulation run. The second type of data is collected during the simulation run at a much higher level of detail. The data for each of these is stored in individual excel files. This enables the user to easily analyse the model data.

4.4 Chapter Summary

This chapter is dedicated to provide information on the simulation model development. The chapter opens in §4.1 with a description of the main functional tractor support services areas and the activities within each of these. A brief process description is also provided in the form of a process flow diagram. In §4.2 the various types of data collected during the course of the project is explained, along with the method of analysis and any assumptions that are included. Lastly, in §4.3 insight is given as to how the various services and the associated data were translated into a simulation model within the *AnyLogic* software.

5 Model Verification and Validation

According to (Banks, 1998), the simulation model developed in the previous chapter needs to be verified and validated. This chapter describes these two steps in the simulation modelling process. The chapter opens in §5.1 by describing the verification of the model. Then, in §5.2 the different measures used to validate the model is provided. The chapter closes in §5.3 with a brief summary.

5.1 Verification

Verification is concerned with the operational model. Its purpose is to ensure that the model is functioning as it should (that is, does the model logic and input data yield sensible results).

Model development was done in the *AnyLogic* software, and the verification was aided in two ways by the software. Firstly, syntax errors are constantly highlighted and any run-time errors can be easily identified through the built-in debugging feature. The second involves the use of animation. *AnyLogic* emphasises the animation and visualisation of simulation models. The model developed in Chapter 4 is no different. Animation was used in order to verify various functions within the model. By animating tractor movement, it is easy to verify that the tractors are moving along the defined paths to the specified production section, as shown in Figure 5.1 with a tractor (circled) *en route* to a production section. This is also useful to ensure that a tractor scheduled for maintenance or those that have experienced a breakdown cannot be utilised to complete any support services. Animation also enables the modeller to verify that the process logic of each support service as shown in Appendix D is indeed executed as intended.

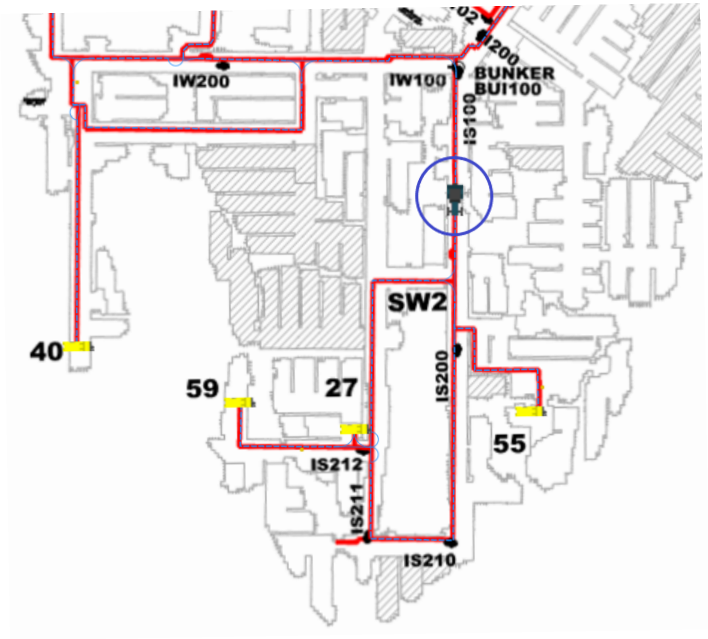

Figure 5.1: Animation depicting tractor movement

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As some of the support services described in the previous chapter are determined by a fixed schedule or predetermined demand rate, it is important to verify that these inputs are accurately reflected within the model logic and the associated output. To verify that the shift system is accurately depicted in the model, the animation of the tractor movement is used concurrently with the state-chart shown in Figure 5.2 below. The current shift is highlighted in red. This should be accurate (according to the actual shift system) when compared to the current time circled in blue. To verify the accuracy of static input rates such as the diesel bowser refill rate, the model output is compared to the expected result to ensure that these inputs are accurately reflected in the model.

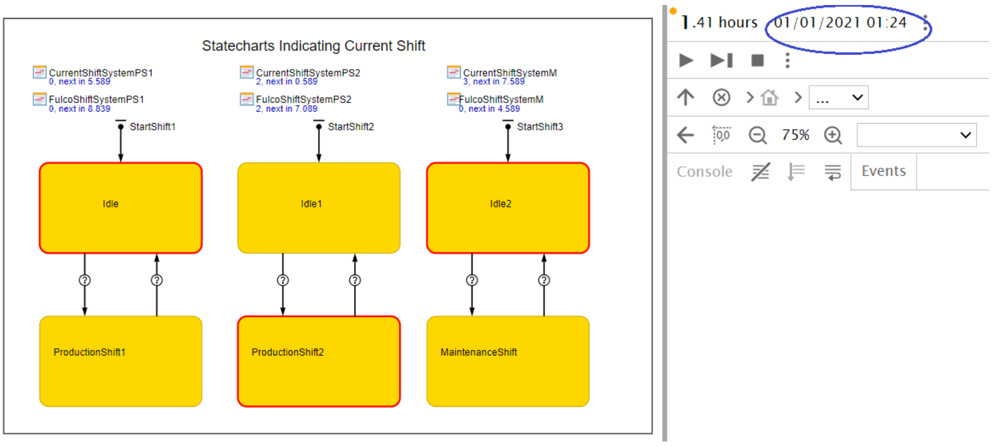

Figure 5.2: Animation depicting the current shift

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Additional verification was done informally through stress testing and by reducing stochastic variables to deterministic variables. Stress testing involved changing various input parameters to extreme values in order to ensure that the model responds in the expected manner. The mining activities at the different production sections that drive the various services was varied by reducing and increasing the tonnes per section per shift. This was done to verify that a decrease or increase in production would indeed reflect a decrease or increase in the demand for the effected services. The number of tractors was also drastically increased and decreased in order to verify that the model is sensitive to capacity changes. Lastly, different input variables were changed from stochastic variables to deterministic variables during certain points in the model translation. This was done in order to monitor the differences in the model output due to changes made elsewhere in the model. By removing any ”noise“ that results from variation caused by stochastic variables one is able to ensure that any difference in output is due to the changes made and not due to variation caused by stochastic variables.

5.2 Validation

Validation seeks to determine whether the simulation model is an accurate representation of the real world system it seeks to emulate. The purpose of validation is to ensure that the model is an accurate substitution for the real world system for the purposes of experimentation (Banks, 1998).

5.2.1 Parameter Variation

Initially parameter variation was done through varying user-determined input values and evaluating the model outcomes. Unlike stress testing, the purpose of parameter variation is not to see how the model reacts to extreme inputs, rather it is used to see whether changes made within the model yield results in line with what can be expected in reality.

The cage is a resource that has a big impact on some of the support services as described in §4.2.3. It is important to determine whether its influence has been accurately incorporated within the simulation model. The two services primarily affected by the availability of the cage are production material deliveries and sub-assembly deliveries. It is therefore reasonable to expect that any changes to the cage (with respect to capacity or the duration of the delay) would directly impact these services. Table 5.1 shows the situation where the capacity of the cage could theoretically be increased to accommodate two machines at a time. As expected this leads to a decrease in the average delivery time for both services.

Table 5.1: Cage capacity parameter variation

Scenario	**Average production material delivery duration**	**Average sub-assembly delivery duration**
Current capacity	4.02 Hours	14.11 Hours
Current capacity + 100%	3.58 Hours	11.32 Hours

Then in Table 5.2 the results are provided for two scenarios, the first is a 50% reduction in the total trip time of a machine inside the cage, the next is a 50% increase. Again, the simulation results reflect what could be expected in reality.

Table 5.2: Cage trip duration parameter variation

Scenario	Average production material delivery duration	Average sub-assembly delivery duration
Current trip time	4.02 Hours	14.11 Hours
Current trip time - 50%	3.39 Hours	7.67 Hours
Current trip time + 50%	19.46 Hours	66.89 Hours

Although parameter variation can be done on a very large number of variables, the discussion is limited to the cage in this chapter as it is an indirect element in the model that has a big influence on the performance of the tractor fleet. The results obtained from varying inputs such as the number of tractors and the shift schedules do yield sensible results, but these are discussed in the subsequent chapters.

5.2.2 Model Output Comparison

The primary method of validation for this simulation model is through a direct comparison of the simulation model output to the real world data. The period under consideration is the 11 month period from 01 July 2020 up to 31 May 2021.

This period was chosen based on a number of factors. Firstly, the availability of historic data at the mine is often limited, hence some of the services do not have any historic data prior to the selected dates. Then, the period cannot extend past 31 May 2021 as this was the last day before the implementation of the Fulco operations. Any information collected beyond this point would be based on data from the Fulco operations. Lastly, because the model does not take the expansion of the mine into account, the period simulated should be over a short term to avoid risking the integrity of the model.

Historic data was collected on the various services over this period and then compared to the output from the simulation model over the same time period. In order to ensure that the results produced are statistically significant, a large number of replications or runs were required. A total of 50 simulation runs were conducted, this is to ensure that the output results can be seen as a statistically significant representation of the model output, accounting for the variability associated with the stochastic elements within the model.

The services included in the validation process is based on the information provided in §4.2. The services that rely on schedules or qualitative estimates are excluded in this comparison (these were verified as described in the previous section). Table E.1 in Appendix E shows the data that was collected over the 11 month period from 01 July 2020 up to 31 May 2021. This data represents the actual performance for each of the services per month. The total amount for the period as well as summary statistics on the monthly performance are included. The data, based on historic performance, was collected from various sources as described in §3.2.

As mentioned, the simulation run is for the same 11 month period. Table E.2 in Appendix E shows the results obtained over the simulation period. These are shown monthly with summary statistics included for each month to illustrate the variation in results over the different replications.

Table 5.3 provides the results obtained over the complete simulation period. The results in both tables reflect the performance of the model after some elementary calibration was performed in order to better reflect the actual performance of the services.

The simulation results and the actual data will be compared in two ways. Qualitatively the average monthly performance will be compared based on the deviation from the actual average. Then the total performance over the period will be statistically compared with the use of an equivalence test. It is important to note that from a practical point of view, a simulation with an accuracy of 90% or a 10% error is deemed acceptable. This allowable error percentage is an arbitrary decision made by subject matter experts at the mine based on the complexity, accuracy and reliability of the input data.

Table 5.3: Simulation total output for 01 July 2020 up to 31 May 2021

	Complete Run	
Support Service	**Total**	**Std. Deviation**
Oil Deliveries (S68 and 320)	322.70	13.44
Production Material Requests	365.36	11.44
Sub Deliveries	1159.36	40.90
Cage Trips	12079.43	337.51
Cage Trips Daily Average	36.12	0.99
Total Tonnes	4179276.31	39944.95
Tonnes/CM/Shift	1048.79	10.51
Tractor Breakdowns (14 Tractors)	205.14	15.70
MTBF (14 Tractors)	551.89	41.81
MTTR (14 Tractors)	20.75	3.66

The accuracy of the simulation model is calculated as a percentage by comparing the absolute difference between the actual data and the simulation performance to the actual data. The simulation error is the complementary percentage of the accuracy of the simulation model.

Qualitative comparison

The number of trips completed per support service, number of breakdowns, the MTBF (hours) and MTTR (hours) are shown as monthly averages for both the simulation model and actual data in Table 5.4 below. The error calculation is shown in Equation 5.1 below.

$$\text{Error} = \frac{|\text{Actual monthly average - Simulation monthly average}|}{\text{Actual monthly average}} \times 100 \quad (5.1)$$

The error is calculated as the absolute difference between the actual data and the simulation output and shown as a percentage.

Table 5.4: Practical comparison for 01 July 2020 up to 31 May 2021

	Simulation-Monthly		**Actual-Monthly**		
Support Services	**Average**	**Std. Deviation**	**Average**	**Std. Deviation**	**Error**
Number of Oil Deliveries (S68 and 320)	29.34	3.54	30.55	7.76	**3.96%**
Number of Production Material Requests	33.21	3.95	35.18	3.49	**5.59%**
Number of Sub Deliveries	105.40	12.15	115.09	9.13	**8.42%**
Number of Cage Trips	1098.13	38.98	1147.73	141.36	**4.32%**
Number of Cage Trips- Daily Average	36.12	1.25	37.02	4.56	**2.45%**
Number of Tractor Breakdowns (14 Tractors)	18.65	5.14	17.64	4.03	**5.74%**
MTBF (14 Tractors)	602.72 Hours	198.05 Hours	572.10 Hours	214.31 Hours	**5.35%**
MTTR (14 Tractors)	20.99 Hours	10.34 Hours	21.43 Hours	9.67 Hours	**2.05%**

From the table it is clear that no service has an error of more than 10%, with the average number of sub-assembly deliveries per month providing the biggest error at only 8.42%. This means that from a practical point, the simulation is within the acceptable error range. These results were also presented to the various subject matter experts at the mine. They concurred that the results seem valid and are a true reflection of the real world operations. This serves as the validation of the model from a more practical perspective.

Statistical comparison

The previous comparison was based on descriptive statistics and a practical examination, based on the deviation from the actual values in combination with the inputs from subject matter experts at the mine. However, validation should also ensure that the results are both practically and statistically significant. In other words, it is important to ensure that the results achieved are not simply due to chance as a result of the stochastic variables in the model.

Traditionally, statistical significance is evaluated through the use of hypothesis testing. If the result of the hypothesis test has achieved a certain level of confidence (95%), it can be deemed statistically significant. The so-called null hypothesis (Ho) for this project can be stated as follows,

$$Ho : \mu_1 = \mu_2$$

here, μ_1 denotes the simulation service performance and μ_2 the actual service performance. The corresponding alternative hypothesis is represented by Ha,

$$Ha : \mu_1 \neq \mu_2.$$

This test seeks to determine whether the population mean, represented by the average over the number of replications is different from the hypothesized mean. In this case the hypothesized mean is represented by the actual historic data. Statistically this hypothesis test can be applied to each of the tractor support services, and using a student t-test with the resulting p-value it can be determined whether the results produced by the simulation model over the period from 01 July 2020 up to 31 May 2021 differs significantly from the actual data over the same period.

However, from a practical point of view there is a 10% simulation error that is deemed acceptable. This tolerance is not incorporated within the hypothesis test. This may subsequently lead to the rejection of the null hypothesis in favour of the alternative hypothesis (that is, it will be decided that the simulation model is not close enough to the reality to be acceptable), when the difference is of no practical difference and the simulation model is in fact providing an accurate representation of the real world scenario. In hypothesis testing, this incorrect rejection of the null hypothesis is also referred to as a *Type I* error.

Equivalence testing is used to see whether under a specified confidence level two means are equal. Within equivalence testing, we are able to specify the allowable difference between two means in order to reflect any differences that are of practical importance. Equivalence testing is popular in fields such as the pharmaceutical industry and psychology (Lourenco and Pinto, 2012, Lakens et al., 2018). The process of equivalence testing involves determining the allowable difference between two means centred around zero (known as the equivalence interval). Then two one-sided t-tests need to be conducted and the resulting p-value evaluated. The hypothesis test can be written as follows:

$$Ho : \text{Lower limit} \geq \mu_1 - \mu_2 \geq \text{Upper limit}.$$

Again, μ_1 denotes the simulation service performance and μ_2 the actual service performance. The corresponding alternative hypothesis represented by Ha,

$$Ha : \text{Lower limit} < \mu_1 - \mu_2 < \text{Upper limit}.$$

In this project the use of equivalence testing is suitable due to the inherent uncertainty associated with any simulation model. The allowable difference of 10% between the actual data and the simulation can be incorporated when defining the equivalence test parameters. It is now possible to ignore any differences that are of no practical significance when validating the model results. The *Minitab* software is used to facilitate the equivalence testing for each of the support services within Table 5.3.

The one-sample equivalence test within the *Minitab* software is used with a 95% confidence level. The sample size is set at 50, reflecting the number of simulation runs. The target value for each of the different tests is the actual total for the data collected over the given period, with the lower- and upper limit calculated by:

$$\text{Lower limit} = 0 - (\text{Target} \times 0.1)$$

$$\text{Upper limit} = 0 + (\text{Target} \times 0.1).$$

As an illustration, the equivalence test for the production material delivery process is described. The hypothesis test is written as follows:

$$Ho : \text{Lower limit} \geq \mu_1 - \mu_2 \geq \text{Upper limit.}$$

Here, μ_1 denotes the total simulated production material deliveries averaged over the various simulation runs, and μ_2 denotes the actual number of production material deliveries for the 11 month period. The corresponding alternative hypothesis represented by Ha,

$$Ha : \text{Lower limit} < \mu_1 - \mu_2 < \text{Upper limit.}$$

The equivalence interval is calculated based on the 10% allowable tolerance. This is shown in Figure 5.3 below.

Method

Target = 387
Lower equivalence limit = -0.1 × target = -38.7
Upper equivalence limit = 0.1 × target = 38.7

Figure 5.3: Equivalence test for production material delivery- Equivalence interval

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The hypothesis test shown in Figure 5.4 conducted according to a 95% confidence interval, yielded a very small p-value. This enables us to reject the null hypothesis in favour of the alternative hypothesis. In other words, we are able to claim that the simulation output is equivalent to the actual production material data.

Test

Null hypothesis: Difference ≤ -38.7 or Difference ≥ 38.7
Alternative hypothesis: -38.7 < Difference < 38.7
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -38.7	49	10.548	0.000
Difference ≥ 38.7	49	-37.309	0.000

The greater of the two P-Values is 0.000. Can claim equivalence.

Figure 5.4: Equivalence test for production material delivery- Hypothesis

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The process is identical for the different services and output data within the simulation model. The full results from the different equivalence tests can be found in Appendix F. These results are summarised in Table 5.5 below. Here the hypothesis test for each support service and the resulting p-value is shown. The table indicates whether or not it is possible to claim equivalence based on the test results.

Table 5.5: Statistical comparison for 01 July 2020 up to 31 May 2021

	Null Hypothesis	**Alternative Hypothesis**	**Resulting p-value**	**Conclusion**
Total number of Oil Deliveries (S68 and 320)	$Ho: -33.6 \geq \mu_1 - \mu_2 \geq 33.6$	$Ha: -33.6 < \mu_1 - \mu_2 < 33.6$	0.000	Reject Ho, can claim equivalence
Total number of Production Material Requests	$Ho: -38.7 \geq \mu_1 - \mu_2 \geq 38.7$	$Ha: -38.7 < \mu_1 - \mu_2 < 38.7$	0.000	Reject Ho, can claim equivalence
Total number of Sub Deliveries	$Ho: -126.6 \geq \mu_1 - \mu_2 \geq 126.6$	$Ha: -126.6 < \mu_1 - \mu_2 < 126.6$	0.001	Reject Ho, can claim equivalence
Total number of Cage Trips	$Ho: -1262.5 \geq \mu_1 - \mu_2 \geq 1262.5$	$Ha: -1262.5 < \mu_1 - \mu_2 < 1262.5$	0.000	Reject Ho, can claim equivalence
Total production tonnes	$Ho: -456281 \geq \mu_1 - \mu_2 \geq 456281$	$Ha: -456281 < \mu_1 - \mu_2 < 456281$	0.000	Reject Ho, can claim equivalence
Average Tonnes/CM/Shift	$Ho: -111.59 \geq \mu_1 - \mu_2 \geq 111.59$	$Ha: -111.59 < \mu_1 - \mu_2 < 111.59$	0.000	Reject Ho, can claim equivalence
Total number of Tractor Breakdowns (14 Tractors)	$Ho: -19.4 \geq \mu_1 - \mu_2 \geq 19.4$	$Ha: -19.4 < \mu_1 - \mu_2 < 19.4$	0.000	Reject Ho, can claim equivalence
Average MTBF (14 Tractors)	$Ho: -57.21 \geq \mu_1 - \mu_2 \geq 57.21$	$Ha: -57.21 < \mu_1 - \mu_2 < 57.21$	0.000	Reject Ho, can claim equivalence
Average MTTR (14 Tractors)	$Ho: -2.14 \geq \mu_1 - \mu_2 \geq 2.14$	$Ha: -2.14 < \mu_1 - \mu_2 < 2.14$	0.000	Reject Ho, can claim equivalence

Upon review of the information presented in Table 5.5, it is concluded that all of the simulation data validated by the use of equivalence testing rejects the null hypothesis (no equivalence) in favour of the alternative hypothesis (the two values are equivalent).

From the practical comparison regarding the monthly performance of the model and the results from the various equivalence tests, it is sufficient to conclude the validation of the simulation model. This model is an accurate representation of the real world operations both from a practical and theoretical perspective.

5.3 Chapter Summary

This chapter highlights the verification and validation of the simulation model developed in the previous chapter. The chapter opens in §5.1 with clarification of the verification of simulation models and how it is done in this project. Then in §5.2, the different methods used to validate the model in order to ensure that it is an accurate reflection of the real world operations are provided.

6 Experimental Design, Analysis and Results

This chapter describes the Fulco operations and the different scenarios that stem from its implementation within the model. The chapter also describes the results obtained by simulating the different scenarios, the subsequent result analysis and recommendations made to the relevant stakeholders. The chapter starts in §6.1 where the Fulco operations and the changes associated with it are explained. Then, §6.2 highlights how these changes were incorporated into the simulation model along with a description of the experimental design. In §6.3, a more detailed description of the different scenarios applied to the simulation model along with the model output from each scenario is provided. Finally, in §6.4 the impact of the Fulco operations is highlighted before a recommendation regarding the tractor fleet at the Bosjesspruit mine is made. The chapter closes in §6.5 with a summary.

6.1 Fulco Operations

The Fulco operations seek to increase the production capability of each mine in the Sasol Mining complex. This will be done through the implementation of a new shift system that will enable 24/7 operations.

With the implementation of Fulco there are a few changes to the current operations at the Bosjesspruit mine. The first major change is the new shift system for both the production sections, as well as the production support services. Sasol Mining currently employs a three shift system comprising of two 10 hour production shifts as well as an overlapping 10 hour maintenance shift. This does not include weekends where the Saturday consists of one production and one services shift, with the Sunday reserved for maintenance. The Fulco shift system has two 12 hour production shifts along with a six hour window shift for every day of the week. The production support services will not follow the same shift system. They will continue to use the three shift system with some minor changes due to operational requirements. These two shift systems are shown graphically in Figure 1.7.

The Fulco shift system increases production in two ways. Firstly, the total number of shifts increases. Then, due to the increased shift length, the total in shift production is also increased.

The second change resulting from the implementation of Fulco is the reduction in the number of production sections at the Bosjesspruit mine. Currently there are nine production sections at the mine. With the implementation of Fulco, there will be a reduction of one production section. This means that the Bosjesspruit mine will have a total of eight production sections.

The effect of these changes on the tractor support services is very uncertain. The demand for services is affected by the new schedule, the increase in productivity as well as the reduction in production sections.

6.2 Simulating the Fulco Operations

In order to use the simulation model to model the Fulco operations, the changes associated with its implementation needs to be incorporated within the simulation model.

The *Schedule* element is used to control the shift days and times. These variables are modified to reflect the 24/7 operations and the new 12 hour shift lengths. This modification automatically enables the simulation model to incorporate the effect of having more shifts on the demand for the tractor support services. However, the in shift productivity needs to be increased.

The assumption is made that the coal production in the different production sections will follow a similar variability profile as depicted in Figure 4.8, but with an overall increase resulting from the longer shifts. The average tonnes per CM per shift (1047.97 Tonnes) for the period described in §4.2.1 was compared to the production forecast (1224 Tonnes) associated with the implementation of the Fulco operations. This comparison provides an increase of 16.8% in production per shift. This increase is introduced within the simulation model inputs.

The reduction in the number of production sections affects the amount of resources and routes within the mine. This is incorporated by removing section P27, shown in Annexure C, from the simulation model.

The simulation model, modified to reflect the Fulco operations, is used to study the effect of the Fulco operations on the tractor fleet requirements. The same 11 month period considered in the validation of the model, 01 July 2020 up to 31 May 2021 will be used. First, metrics resulting from the simulation model under the current shift system will serve as a baseline.

The baseline will then be compared against the simulation model under Fulco operations. Initially, the only parameter that will be modified is the modification of the model to reflect the Fulco operations. The tractor fleet composition will remain constant. Hereafter, different variables such as the number of tractors, the support services shift times and the management policy will be modified to simulate different scenarios.

6.3 Scenario Formulation and Results

This section provides more detail regarding the different scenarios that were considered by the simulation model and the results achieved for each of these. The results obtained from the baseline are documented and explained. Then different scenarios under the Fulco operations are described.

Different metrics are used to evaluate the performance of the tractor fleet. However, considering the practical characteristics of the different support services, the primary metric will be the number of hours that the Bosjesspruit mine has to wait for production material. As previously mentioned, production material is critical in providing secondary roof support and any delay in availability of the material will directly lead to production losses. Additionally, the service level achieved by the tractor fleet in providing production support material is used when comparing the performance of different scenarios.

Together with the delay in delivery of production materials and the associated service level, similar metrics are tracked for the remaining support services. However, delays in the delivery of these services do not directly lead to production losses and serve as a secondary comparison between scenarios.

6.3.1 Baseline Scenario

The current operations serve as the baseline scenario. In this scenario, the current shift system is incorporated into the simulation model. The tractor fleet composition is also identical to the current operations.

There are a total of 14 tractors across the various departments. The logistics department consists of two tractors responsible for production material, oil and diesel deliveries. The road building department has five tractors available for road building and dust suppression. There are five tractors available for stone dusting and two tractors for sub-assembly deliveries. Table 6.1 provides a summary of the tractor fleet composition under the baseline scenario, the table also indicates the different shift systems that the departments are using.

Table 6.1: Tractor fleet composition- baseline scenario

Department	**Fleet Size**	**Shift System**
Logistics	2	Two 10 hour Shifts, 5 Days/week
Road building	5	One 10 hour Shift, 5 Days/week
Stone dusting	5	Two 10 hour Shifts, 5 Days/week
Sub-assemblies	2	Three 8 hour Shifts, 5 Days/week
Total	14	-

The output data is compared to real-world observations and the knowledge of subject matter experts at the mine. The performance delivered during the baseline model runs will serve as the basis for comparisons between scenarios.

Table 6.2, provides more detail around the late deliveries. The total number of occurrences indicate how many times a delivery is deemed late according to the specific services' criteria. The duration of late deliveries indicates how many hours were lost due to late deliveries. An important figure to take note of is the number of hours waiting for production material (97.6 Hours). The wait for production material can be directly translated into hours of production lost at the mine.

Table 6.2: Baseline scenario- Performance

Service	Average number of late deliveries	Average total duration of late deliveries
Production material deliveries	5.02	97.60 Hours
Oil deliveries	2.88	67.75 Hours
Diesel deliveries	8.46	71.72 Hours
Road building	23.76	248.84 Hours
Stone dusting	0.62	NA (Schedule)
Sub-assembly deliveries	398.16	6046.48 Hours

The service level of each support service is shown in Table 6.3 below. The service level of the production material deliveries (98.62%) serves as a comparison between the simulation output of the different scenarios considered in this section.

Table 6.3: Baseline scenario- Service level

Service	Average service level
Production material deliveries	98.62%
Oil deliveries	99.11%
Diesel deliveries	92.43%
Road building	91.03%
Stone dusting	99.95%
Sub-assembly deliveries	66.13%

The results obtained from the running of the simulation model under the baseline conditions serve as the minimum requirements that need to be met for any possible recommendation regarding the tractor fleet under the Fulco operations.

6.3.2 Fulco Operations

The approach used to dictate the different scenarios tested is of a practical and logical nature. A scenario is proposed by the subject matter experts at the mine, and this is then simulated by the model. The results obtained from the model are evaluated. Once the results have been evaluated, the scenario is refined. Two metrics, the number of hours lost due to late material deliveries and the production material service level, will be used to compare the tractor fleet performance between the different scenarios. Metrics from the remaining tractor support services will serve as a secondary comparison when comparing the tractor fleet performance under different scenarios.

In order to understand the effect of the Fulco operations on the tractor fleet and the support services they offer, it is important to incorporate the Fulco operational changes into the model. These changes are described in detail in §6.2.

Fulco Operations Scenario- Fulco 0

In the first scenario, referred to as *Fulco 0*, the only changes to the simulation model are those associated with the implementation of the Fulco operations. Table 6.4 provides a summary of the tractor fleet composition under the *Fulco 0* scenario. The table also indicates the different shift systems that the departments are using under the Fulco operations. Under the Fulco operations, the shift lengths are increased from 10 hours to 12 hours for each support service department. There are also changes regarding the number of shifts for the Road building and Sub-assembly department.

Table 6.4: Tractor fleet composition- *Fulco 0* scenario

Department	**Fleet Size**	**Shift System**
Logistics	2	Two 10 hour Shifts, 5 Days/week
Road building	5	Two 10 hour Shift, 5 Days/week
Stone dusting	5	Two 10 hour Shifts, 5 Days/week
Sub-assemblies	2	Two 12 hour Shifts, 5 Days/week
Total	14	-

Under the *Fulco 0* scenario, the fleet composition is kept the same as in the baseline scenario. Table 6.5 indicates the performance of the support services in this scenario.

Table 6.5: *Fulco 0* scenario- Performance

Service	**Average number of late deliveries**	**Average total duration of late deliveries**	**Average service level**
Production material deliveries	135.80	2248.30 Hours	74.42%
Oil deliveries	115.26	1381.99 Hours	75.72%
Diesel deliveries	34.48	625.50 Hours	75.48%
Road building	136.90	2498.50 Hours	66.47%
Stone dusting	0.80	NA (Schedule)	99.95%
Sub-assembly deliveries	260.86	3458.60 Hours	77.85%

These results are in line with what is expected with the implementation of the Fulco operations. With the move to 24 hour production, there is an increase in demand for all of the support services. This increase is reflected by the dramatic increase in delays as a result of late deliveries (hours lost due to production material delivery delays are up to 2248.3 hours). This performance is mirrored in the service level of the production material deliveries (74.42% compared to 98.62% in the baseline). The performance of the Stone dusting department remains unaffected as the service follows a schedule. Whilst the sub-assembly delivery performance actually improved, this is expected as there is one fewer production section and longer shifts with fewer changeovers.

Fulco Operations Scenario- Fulco 1

The second scenario, is referred to as *Fulco 1*. In this scenario, the aim is to negate the negative effects that the implementation has on the tractor fleet according to the results shown in the *Fulco 0* scenario by increasing the number of tractors within the tractor fleet. The number of tractors to add, and in which area to add them is not a trivial matter. Based on several constraints at the mine, it is decided that a maximum number of four additional tractors can be added. The decision to test four tractors is based on the number of additional resources (both tractors and labour) that can be made available at the mine. Due to operational considerations, these tractors are divided evenly between the Road building and Logistics departments. These departments are also those that are most affected by the introduction of the Fulco operations as shown in their performance under the *Fulco 0* scenario. The shifts for each service remain unchanged. The tractor fleet composition under this scenario is shown in Table 6.6.

Table 6.6: Tractor fleet composition- *Fulco 1* scenario

Department	**Fleet Size**	**Shift System**
Logistics	4	Two 10 hour Shifts, 5 Days/week
Road building	7	Two 10 hour Shift, 5 Days/week
Stone dusting	5	Two 10 hour Shifts, 5 Days/week
Sub-assemblies	2	Two 12 hour Shifts, 5 Days/week
Total	18	-

Table 6.7 indicates the performance of the support services in this scenario. With the four additional tractors there is an improvement within the performance of the tractor support services. There is a reduction in delays as a result of late deliveries, hours lost due to production material delivery delays are down to 1409.32 when compared to the 2248.3 hours under the *Fulco 0* scenario. This reduction in delays due to late deliveries is mirrored in the rest of the services provided by the Logistics department and the Road building department. The service levels for both the Logistics department and the Road building department also indicate a slight improvement, with a service level of 78.29% for production material deliveries.

Table 6.7: *Fulco 1* scenario- Performance

Service	**Average number of late deliveries**	**Average total duration of late deliveries**	**Average service level**
Production material deliveries	116.26	1409.32 Hours	78.29%
Oil deliveries	103.60	985.05 Hours	78.16%
Diesel deliveries	28.66	514.86 Hours	77.91%
Road building	118.08	2098.27 Hours	71.12%
Stone dusting	0.88	NA (Schedule)	99.95%
Sub-assembly deliveries	254.06	2770.03 Hours	78.28%

However, this improvement is minimal considering the amount of capital required to finance the additional tractors and the additional labour required to operate them. When reviewing the reduction in time lost due to delayed deliveries and the small improvement in service levels, it is clear that increasing the number of tractors will not sufficiently improve the performance of the support services.

Fulco Operations Scenario- Fulco 2

One of the ways that the implementation of the Fulco operations will increase overall production is by increasing the number of shifts (24/7 operations). This creates demand for the support services during times (weekends), when under the current schedule, no tractors are available to satisfy this demand. It is evident from *Fulco 1* that additional tractors do not fully negate this scheduling problem.

In the scenario, referred to as *Fulco 2* the schedules of the tractor support services are modified. Under this scenario the fleet size is kept the same as under the baseline scenario. However, the schedules of the Logistics and Road building departments are modified to include an additional day shift over weekends. The tractor fleet composition and shift modifications under this scenario are shown in Table 6.8.

Table 6.8: Tractor fleet composition- *Fulco 2* scenario

Department	**Fleet Size**	**Shift System**
Logistics	2	Two 10 hour Shifts, 5 Days/week + DS on weekends
Road building	5	Two 10 hour Shift, 5 Days/week + DS on weekends
Stone dusting	5	Two 10 hour Shifts, 5 Days/week
Sub-assemblies	2	Two 12 hour Shifts, 5 Days/week
Total	14	-

By extending the availability of the tractors to include weekends, the tractor fleet capacity is increased. This is reflected in the striking performance improvement of the Logistics and Road building departments.

Table 6.9 indicates the performance of the support services in this scenario. There is a very big reduction in delays as a result of late deliveries. Hours lost due to production material delivery delays are down to 69.81 when compared to the 2248.3 hours under the *Fulco 0* scenario. The service level of production material deliveries is up to 97.61%.

Table 6.9: *Fulco 2* scenario- Performance

Service	Average number of late deliveries	Average total duration of late deliveries	Average service level
Production material deliveries	12.84	69.81 Hours	97.61%
Oil deliveries	5.68	29.09 Hours	98.80%
Diesel deliveries	1.88	16.25 Hours	98.60%
Road building	11.70	62.15 Hours	97.14%
Stone dusting	0.94	NA (Schedule)	99.95%
Sub-assembly deliveries	256.86	3864.24 Hours	78.83%

This big reduction in delays due to late deliveries and increased service levels confirms that the decrease in performance of the tractor support services under the Fulco operations is due to the additional production shifts over weekends and the timing of demand for the support services during this window.

Fulco Operations Scenario- Fulco Pooled 0

The simulation model provides a lot of flexibility in terms of experimenting with tractor fleet composition and schedules. Another scenario that is deemed to be worthy of investigation is to pool tractors amongst different departments. This means that a tractor, usually allocated to a particular department, can be used to perform a support service in a different department. The simulation model provides a platform to test this scenario without risking severe operational disruptions at the mine.

The scenario called *Fulco Pooled 0* seeks to determine what effect the pooling of tractors will have on the tractor fleet performance under the Fulco operations. Due to operational considerations, the only tractors that can be pooled together are those in the Logistics and Stone dusting departments. The fleet size and schedules are kept constant for this scenario. This is shown in Table 6.10.

Table 6.10: Tractor fleet composition- *Fulco Pooled 0* scenario

Department	**Policy**	**Fleet Size**	**Shift System**
Logistics + Stone dusting	Pooled	7	Two 10 hour Shifts, 5 Days/week
Road building	No pooling	5	Two 10 hour Shift, 5 Days/week
Sub-assemblies	No pooling	2	Two 12 hour Shifts, 5 Days/week
Total	-	14	-

The performance of the tractor fleet is shown in Table 6.11. Again, the results confirm that the reduction in performance is due to the demand for support services over weekends. However, the pooling of tractors in the Logistics and Stone dusting departments does yield an improvement in performance when comparing results against the *Fulco 0* scenario. The hours lost due to production material delivery delays are down to 1169.11 when compared to the 2248.3 hours under the *Fulco 0* scenario. The service level is increased slightly to 78.71%.

Table 6.11: *Fulco Pooled 0* scenario- Performance

Service	**Average number of late deliveries**	**Average total duration of late deliveries**	**Average service level**
Production material deliveries	113.82	1169.11 Hours	78.71%
Oil deliveries	102.32	943.03 Hours	78.38%
Diesel deliveries	27.52	476.37 Hours	78.85%
Road building	134.60	2262.15 Hours	72.15%
Stone dusting	0.64	NA (Schedule)	99.97%
Sub-assembly deliveries	270.96	3520.75 Hours	76.93%

Fulco Operations Scenario- Fulco Pooled 1

Once again, the schedules of the Logistics and Road building departments are modified to mitigate the mismatch in schedules from production sections compared to the support services. The *Fulco Pooled 1* scenario incorporates the modification in schedules with the pooling of the Logistics and Stone dusting tractors. Table 6.12 defines this scenario.

Table 6.12: Tractor fleet composition- *Fulco Pooled 1* scenario

Department	**Policy**	**Fleet Size**	**Shift System**
Logistics + Stone dusting	Pooled	7	Two 10 hour Shifts, 5 Days/week + DS on weekends
Road building	No pooling	5	Two 10 hour Shift, 5 Days/week + DS on weekends
Sub-assemblies	No pooling	2	Two 12 hour Shifts, 5 Days/week
Total	-	14	-

The performance of the tractor fleet is shown in Table 6.13. The performance obtained from this scenario is excellent, with virtually no time lost as a result of delays in the delivery of services. The hours lost due to production material delivery delays are almost zero compared to the 2248.3 hours under the *Fulco 0* scenario. The service levels for the different support services confirm that under the *Fulco Pooled 1* scenario a very high level of performance is achievable.

Table 6.13: *Fulco Pooled 1* scenario- Performance

Service	**Average number of late deliveries**	**Average total duration of late deliveries**	**Average service level**
Production material deliveries	0.02	0.01 Hours	99.90%
Oil deliveries	0.00	0.00 Hours	100%
Diesel deliveries	0.02	0.01 Hours	99.90%
Road building	11.28	71.28 Hours	97.20%
Stone dusting	0.00	NA (Schedule)	100%
Sub-assembly deliveries	257.86	3253.75 Hours	78.83%

Fulco Operations Scenario- Fulco Pooled 2

The performance results uncovered upon analysis of the *Fulco Pooled 1* scenario creates the precedence to investigate whether it is possible to maintain the high level of performance whilst reducing the number of tractors in the Logistics and Stone dusting pool. The last scenario, referred to as *Fulco Pooled 2* seeks to determine this. Once again, operational and practical considerations, including labour commitments and existing investments, dictate that only one tractor can be removed from the tractor pool. The fleet composition for this scenario is provided in Table 6.14.

Table 6.14: Tractor fleet composition- *Fulco Pooled 2* scenario

Department	**Policy**	**Fleet Size**	**Shift System**
Logistics + Stone dusting	Pooled	6	Two 10 hour Shifts, 5 Days/week + DS on weekends
Road building	No pooling	5	Two 10 hour Shift, 5 Days/week + DS on weekends
Sub-assemblies	No pooling	2	Two 12 hour Shifts, 5 Days/week
Total	-	13	-

The performance of the tractor fleet is shown in Table 6.15. The performance obtained from this scenario is still very good, surpassing the baseline performance easily. There is almost no time lost as a result of delays in the delivery of services. The hours lost due to production material delivery delays are almost negligible compared to the 2248.3 hours under the *Fulco 0* scenario. Again, the service level for the services provided by the Logistics and Stone dusting departments is excellent.

Table 6.15: *Fulco Pooled 2* scenario- Performance

Service	**Average number of late deliveries**	**Average total duration of late deliveries**	**Average service level**
Production material deliveries	0.20	0.18 Hours	99.90%
Oil deliveries	0.06	0.04 Hours	99.90%
Diesel deliveries	0.00	0.00 Hours	100%
Road building	11.48	62.51 Hours	97.17%
Stone dusting	0.20	NA (Schedule)	99.90%
Sub-assembly deliveries	244.84	2949.55 Hours	79.01%

When the tractors within the Logistics and Stone dusting departments are pooled, combined with the adjusted schedule for the Logistics and Road building departments, the results from the *Fulco Pooled 2* scenario indicate that there is a definite opportunity to reduce the number of tractors in the tractor fleet.

6.3.3 Scenario Performance Summary

Including the baseline, seven different scenarios are considered by the simulation model. The detailed results of each are described in the preceding sections. Table 6.16 provides a summary of each scenario and the respective performance under the primary metric (the duration of late production material deliveries).

Table 6.16: Scenario summary

Scenario	**Fleet size**	**Logistics**	**Stone dusting**	**Road building**	**Sub-assemblies**	**Duration of late deliveries- Production Material**
Baseline	14	2	5	5	2	97.60 Hours
Fulco 0	14	2	5	5	2	2248.30 Hours
Fulco 1	18	4	5	7	2	1409.32 Hours
Fulco 2	14	2	5	5	2	69.81 Hours
Fulco Pooled 0	14	7		5	2	1169.11 Hours
Fulco Pooled 1	14	7		5	2	0.01 Hours
Fulco Pooled 2	13	6		5	2	0.18 Hours

When comparing the results from the different scenarios to the baseline, there are a few scenarios that show improved performance. Table 6.17, provides a summary of each scenario compared to the baseline, indicating whether or not there is an improvement (decrease in delays) or a reduction (increase in delays) in performance. The performance summary, shown as a percentage, is based on the primary metric- the duration of late deliveries for production material of the scenario compared to the baseline. A performance summary percentage less or equal to the baseline ($\leq$ 100%) indicates improved performance under that scenario, whilst anything more than the baseline ($>$ 100%) indicates a reduction in performance.

Table 6.17: Scenario summary compared to baseline

Scenario	**Performance**	**Baseline Performance**	**Performance Summary**	**Conclusion**
Fulco 0	2248.30 Hours	100% (97.60 Hours)	+ 2204%	Reduced performance
Fulco 1	1409.32 Hours	100% (97.60 Hours)	+ 1344%	Reduced performance
Fulco 2	69.81 Hours	100% (97.60 Hours)	- 29%	Improved performance
Fulco Pooled 0	1169.11 Hours	100% (97.60 Hours)	+ 1098%	Reduced performance
Fulco Pooled 1	0.01 Hours	100% (97.60 Hours)	- 99%	Improved performance
Fulco Pooled 2	0.18 Hours	100% (97.60 Hours)	- 99%	Improved performance

6.4 Recommendation

This section aims to analyse the scenarios considered and modelled with the simulation model and then make a recommendation in terms of the tractor fleet composition at the Bosjesspruit mine, based on performance results.

The effect that the implementation of the Fulco operations will have on the tractor fleet is clear when analysing the *Fulco 0* scenario. Compared to the baseline performance, it is clear that there is a substantial drop in performance under the Fulco operations. The simulation model indicates that a lot of delays can be expected as a result of late deliveries. In other words, the tractor fleet will not be able to handle the additional demand and negate the schedule misalignments that come with the Fulco operations with the current fleet configuration.

The performance of each of the different scenarios is graphically shown in Figure 6.1. The orange bars indicate the average amount of time waiting for production material as a result of late deliveries, whilst the blue dots indicate the tractor fleet size. The green bars indicate the scenarios that have outperformed the baseline performance results. When reviewing the performance data obtained from the different scenarios it is clear that in order to mitigate the effects of the Fulco operations, additional shifts need to be incorporated into the Logistics and Road building departments. This result is further validated when considering the fact that other Sasol Mines are currently using overtime on weekends to account for the performance shortfall experienced after implementing Fulco operations. When the tractors are pooled together in the Logistics and Stone dusting departments, there is an opportunity to reduce the tractor fleet by one tractor. This reduction has substantial economic benefits. Not only does this reduce the costs associated with the tractor, there is also a reduction is labour costs with less operators required.

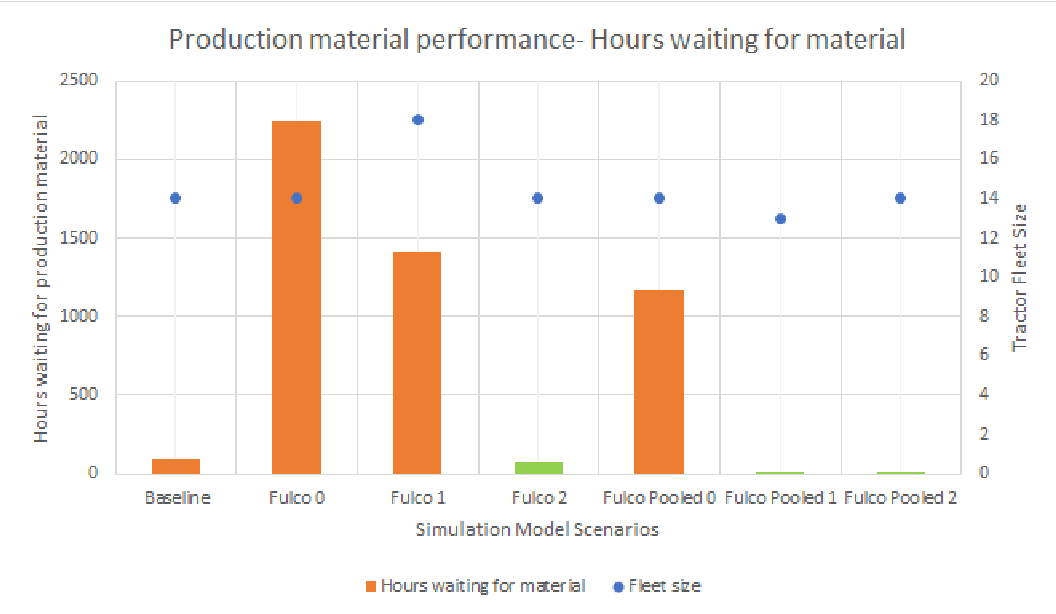

Figure 6.1: Scenario performance graphic

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Based on the model output, it is recommended that the tractor fleet be reduced by one tractor, to 13 tractors. The Logistics and Stone dusting tractors should be pooled together. Importantly, additional shifts (or overtime in the short term) need to be introduced over weekends. This recommendation will not only mitigate the adverse effects of the Fulco operations, but improve overall performance when comparing results to the baseline.

6.5 Chapter Summary

This chapter is dedicated to provide information on the Fulco operations and how the simulation model is used to simulate the effects that come with the various changes. The chapter opens in §6.1 with a description of the Fulco operations and the resulting changes at the Bosjesspruit mine. Then, in §6.2 the manner in which these changes are incorporated into the simulation model is provided. This section also describes the approach that is taken to use the simulation model to study the effects of the Fulco operations on the tractor fleet. This chapter also highlights the different scenarios modelled with the previously developed simulation model. The rationale of each scenario and its results are shown in §6.3, before the different scenarios and their performance are summarised. In §6.4 the effect of the Fulco operations on the tractor fleet is highlighted. The section ends with a recommendation on the tractor fleet composition.

7 Conclusion

This chapter is the final chapter of this project. It opens in §7.1 with a summary that highlights the fulfilment of the objectives laid out in the introductory chapter. This is followed by §7.2 with an appraisal of the work completed in this project. Lastly, §7.3 provides a recommendation for future work pertaining to this project.

7.1 Project Summary

This project consists of seven chapters, including this final chapter. The first chapter, Chapter 1, provides the reader with some background information on the coal mining environment before introducing the problem statement and the objectives of this project.

Chapter 2 addresses Objectives I(a)-(d) of §1.4. This chapter contains a thorough literature review related to the fleet sizing problem. The various solution approaches and applications of the fleet sizing problem are described in this chapter. A critical analysis of the different methods available to solve the fleet sizing problem is an important result of this literature review.

Chapter 3, describes the research methodology that was followed in the pursuit of developing a solution to the problem described in §1.2. This chapter further motivates simulation as the solution approach by considering the analysis of the literature review along with the dynamic and the complex nature of the problem at hand. A well known methodology used to solve simulation modelling problems and how to apply this methodology to this project is presented in this chapter.

Chapter 4 describes the model development process. This chapter addresses Objectives II-III of §1.4. The various tractor support services are described in form and function. This is according to the operations at the Bosjesspruit mine before the implementation of the Fulco operations. The various data collection and analysis methods are described in this chapter before the translation of the model into the *AnyLogic* software is documented.

In Chapter 5, the verification and validation of the simulation model is described in fulfilment of Objective IV of §1.4. Verification of the model includes the use of *AnyLogic* software features such as syntax error identification and animation. This is also aided by stress testing and by changing stochastic variables to deterministic variables. The different validation methods are highlighted including parameter variation. The primary validation technique, that of comparing model results with the real-world operations is described in detail from both a qualitative and a statistical viewpoint.

The next chapter, Chapter 6, provides the reader with more information on the Fulco operations. The changes experienced by the tractor support services as a result of its implementation are highlighted. The adaptation of the simulation model to the Fulco operations and any accompanying assumptions are described in this chapter. Additionally, the different scenarios modelled under the Fulco operations are detailed before the output of the simulation model and the recommendations that stem from the analysis of the results are provided to the reader. The scenario analysis is in fulfilment of Objectives V-VI of §1.4. Initially the baseline performance of the tractor fleet according to specified metrics is determined by modelling the current operations at the Bosjesspruit mine. Then six different scenarios are modelled, are all based on the Fulco operations. The results from each scenario are documented and critically analysed. From the output data and the subsequent performance review, a recommendation is made to the stakeholders at the mine.

7.2 Project Appraisal and Recommendations

The work documented in this report culminated in the development of a simulation model, simulating the tractor support services at the Bosjesspruit mine. This model recreates each support service and various other elements of the mine in order to simulate the tractor operations.

This model proves that simulation modelling can be a technique that provides the end-user with reliable output data when considering different solution approaches to the fleet sizing problem. In literature there is very limited use of simulation modelling to model support services of mining operations, with the primary focus being on production activities.

As input, the model takes demand data in different forms for each support service, information specific to the Bosjesspruit mine and where applicable, assumptions based on observations or inputs from stakeholders. The output of the model indicates the performance of the different tractor support services based on these different input parameters. This indicates how the support services will react under different scenarios in a very dynamic and uncertain environment.

The simulation model addresses the research question posed in §1.3 by using a simulation model to assess the impact of the Fulco operations on the support services and subsequently, the tractor fleet size. Based on the simulation model output, it is clear that there is a substantial drop in performance under the Fulco operations. By using the simulation model to model the Fulco operations, the mine can plan for the expected increase in delays as a result of the decrease in performance of the tractor fleet. The simulation model provides an early indication that the tractor fleet will not be able to handle the additional demand and negate the schedule misalignments with the current fleet configuration.

This model serves as a tool for decision making in a very high pressure and uncertain operating environment. By mitigating the risks associated with testing different scenarios in the real-world operations at the mine, and allowing the safe analysis of the impact of the Fulco operations on the tractor support services, the model enables the different stakeholders to test different scenarios without jeopardizing the operational performance of the mine. Several scenarios were brought forward for testing by the stakeholders at the mine. Based on the simulation model output and subsequent analysis of each scenario, a number of recommendations can be made:

I The tractor fleet will not be able to handle the additional demand and negate the schedule misalignments with the current fleet configuration.

II In the short term, schedule misalignments can be mitigated by utilising overtime over weekends.

III A push system can be employed for material delivery, enabling the delivery of material before weekends to ensure material availability.

IV Once operations have stabilised after the implementation of Fulco, the option of pooling tractors can be considered.

V The simulation model indicates that by utilising additional shifts over weekends and by pooling tractors, the tractor fleet can be reduced whilst improving performance.

7.3 Suggestions for Future Work

This section is dedicated to provide clarification of possible future work that may be pursued in respect of the work documented in this report. This is in fulfilment of Objective VII of §1.4. These suggestions were not pursued during this project, either because of time constraints or scope limitations.

I There are several assumptions and simplifications in the simulation model. If reviewed and refined, these can create adequate room for improvement in the simulation model.

II The simulation model is based on data from the Bosjesspruit mine, so its usability is currently limited to this mine. There is an opportunity to create a more generic model, applicable to similar operations. The model can then serve as a tool for decision making at other mines.

III The Fulco operations are to be implemented across Sasol Mining during 2021. The model can be further refined by comparing the model output results to those achieved under the Fulco operations once implemented.

IV In this project a very simplistic performance criteria is used to evaluate and compare different scenarios. A performance measurement framework can be developed to improve the comparison between the output of different scenarios.

V Lastly, other than simulation, a different solution approach can be investigated. A different solution approach such as those described in Chapter 2 can be used to compare results.

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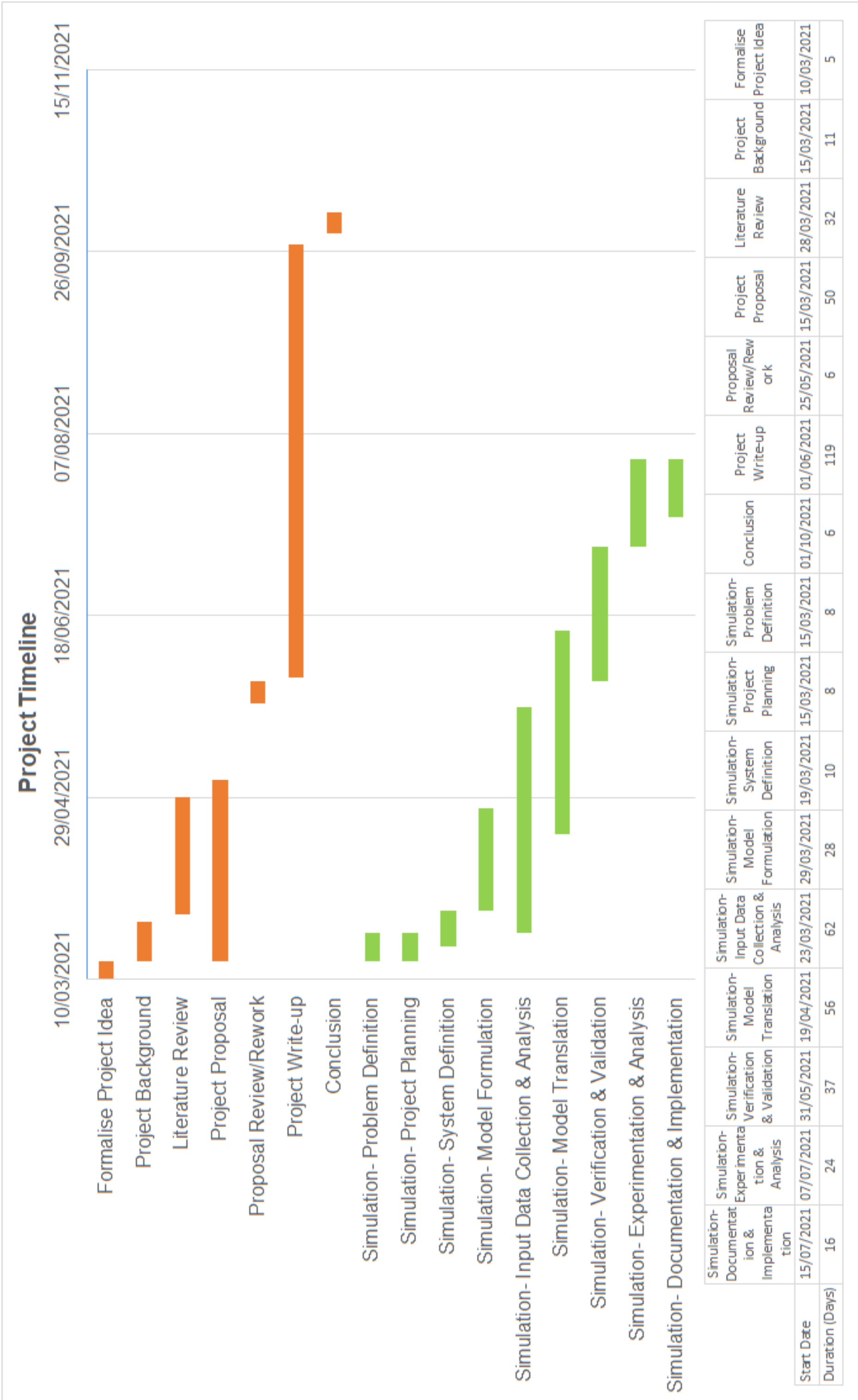
APPENDIX A Project Timeline

The expected timeline is given in Figure A.1 in Gantt-chart form.



	Start Date	Duration (Days)
Simulation- Documentation & Implementation	15/07/2021	16
Simulation- Experimentation & Analysis	07/07/2021	24
Simulation- Verification & Validation	31/05/2021	37
Simulation- Model Translation	19/04/2021	56
Simulation- Input Data Collection & Analysis	23/03/2021	62
Simulation- Model Formulation	29/03/2021	28
Simulation- System Definition	19/03/2021	10
Simulation- Project Planning	15/03/2021	8
Simulation- Problem Definition	15/03/2021	8
Conclusion	01/10/2021	6
Project Write-up	01/06/2021	119
Proposal Review/Rework	25/05/2021	6
Project Proposal	15/03/2021	50
Literature Review	28/03/2021	32
Project Background	15/03/2021	11
Formalise Project Idea	10/03/2021	5

Figure A.1: Expected project timeline

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APPENDIX B Tractor Services

Table B.1 represents the list of the tractor services that will form part of this project. These service are included as their operations are likely to be affected by the introduction of the Fulco operations.

Table B.1: Tractor services included

	Service	Description
1	Production material	Production material delivered to production sections as mining advances, including roof bolts, roof bolt resin (used in support) and picks.
2	Diesel	Delivery of diesel at various underground locations
3	Oil	Delivery of oil at various underground locations
4	Sub assemblies	Delivery and collection of machine or equipment sub-assemblies
5	Stone dusting	Stone dusting in newly mined areas or travel roads
6	Road building	Gravel delivery in road building operations

Table B.2 is provided for comprehensiveness, these services are also provided by tractors. However, these are not affected by the Fulco operations and they are abstract in nature, making them impossible to include in any simulation model as little to no information is available.

Table B.2: Tractor services excluded

	Service	Description
1	Cables	Delivery and collections of repaired/broken cables
2	Water handling	Movement of equipment in the water handling of the mine
3	11 Kv	Enabling the reclamation and installation of 11Kv infrastructure
4	Section Belts	Movement of equipment or material in the extension of section belts
5	Main Belts	Movement of equipment or material in the extension of main belts
6	Welding	Movement of equipment or material to be used for welding
7	Explosives	Delivery of explosives to the required areas
8	Telemetric	Enabling the installation of telemetric infrastructure

APPENDIX C Bosjesspruit Mine

The underground layout of the Bosjesspruit mine, Irenedale shaft, is shown in Figure C.1. The red lines indicate travelling roads throughout the mine, whilst the numbers indicate the locations of the different production sections.

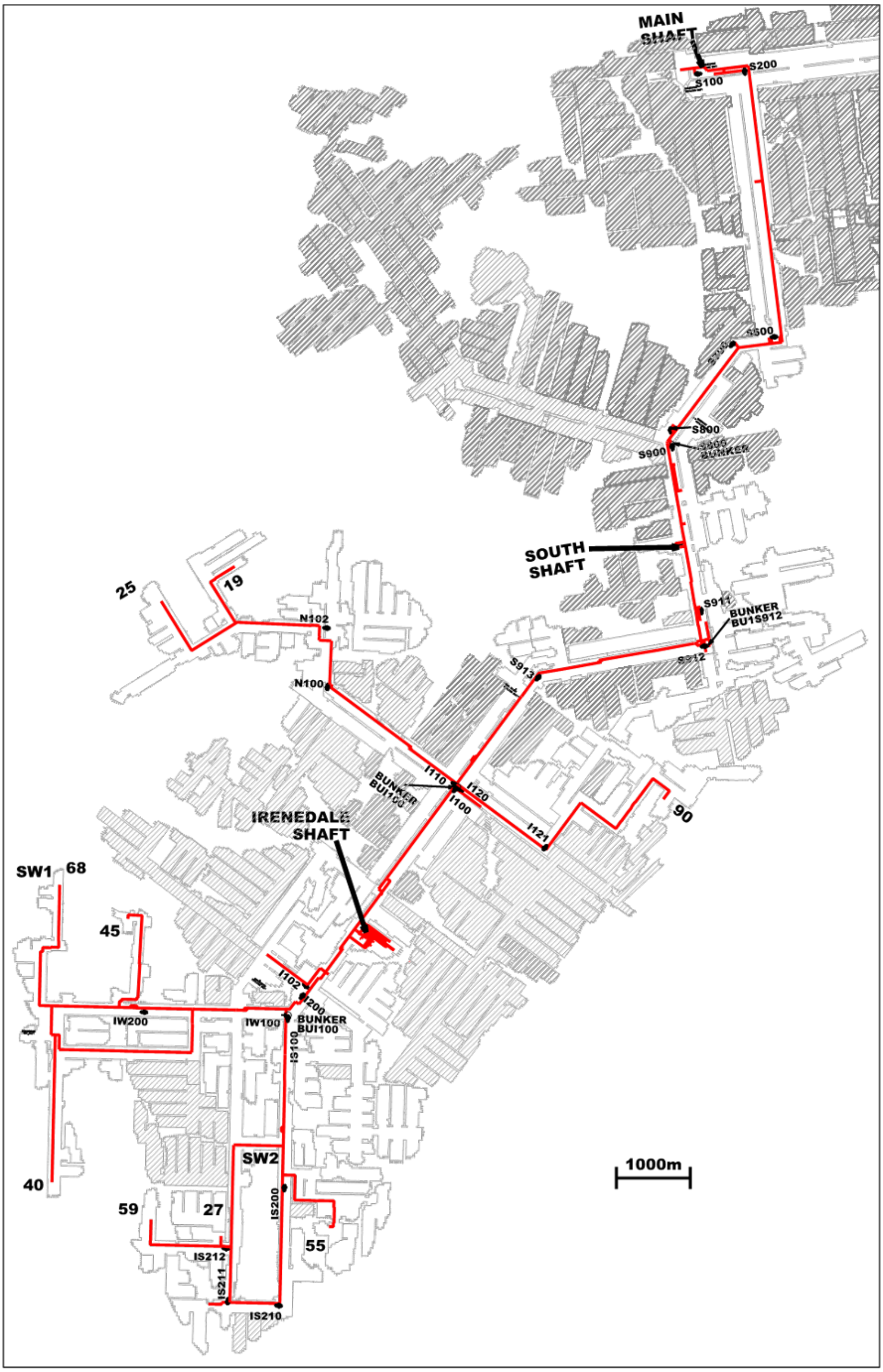

Figure C.1: Bosjesspruit mine layout

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APPENDIX D Process Models

The individual processes for each support service within the *AnyLogic* software are shown for each of the main functional areas.

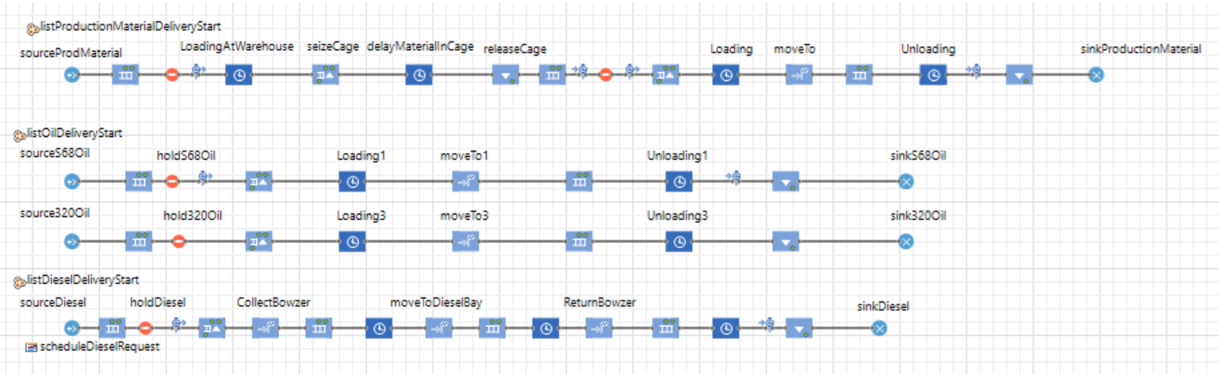

Figure D.1: *AnyLogic* process depiction of the logistic department

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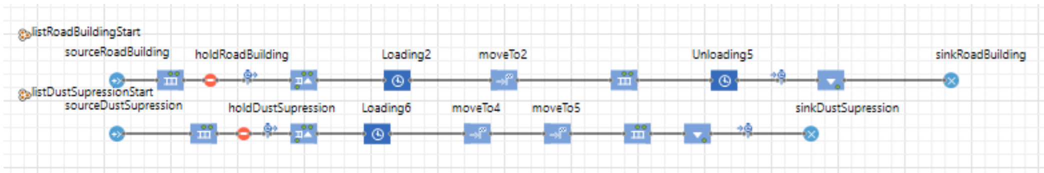

Figure D.2: *AnyLogic* process depiction of the road building department

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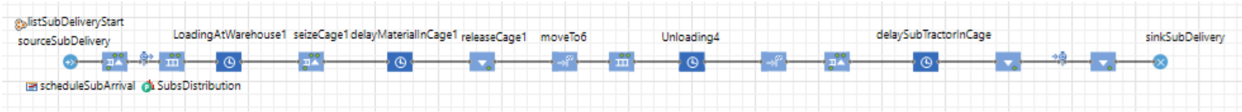

Figure D.3: *AnyLogic* process depiction of the sub-assembly delivery process

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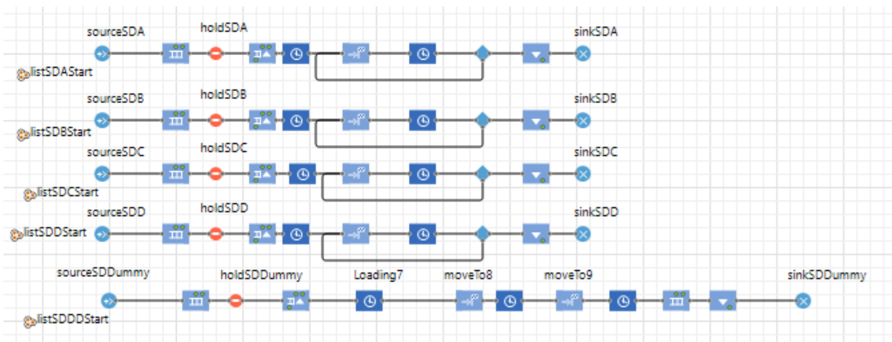

Figure D.4: *AnyLogic* process depiction of the stone dusting process

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APPENDIX E Model Validation Data

Table E.1 shows the actual data that was collected over the 11 month period from 01 July 2020 up to 31 May 2021. This data represents the actual performance for each of the services per month.

Table E.1: Actual data for 01 July 2020 up to 31 May 2021

Support Service	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20	Jan-21	Feb-21	Mar-21	Apr-21	May-21	**Total**	**Average**	**Std. Deviation**
Oil Deliveries (S68 and 320)	25.00	24.00	36.00	28.00	39.00	11.00	37.00	33.00	36.00	32.00	35.00	**336**	**30.55**	**7.76**
Production Material Requests	30.00	28.00	35.00	39.00	37.00	36.00	35.00	33.00	40.00	38.00	36.00	**387**	**35.18**	**3.49**
Sub Deliveries	104.00	107.00	104.00	115.00	123.00	107.00	119.00	118.00	114.00	136.00	119.00	**1266**	**115.09**	**9.13**
Cage Trips	1245.00	1359.00	1320.00	1066.00	1239.00	834.00	1124.00	1025.00	1173.00	1071.00	1169.00	**12625**	**1147.73**	**141.36**
Cage Trips Daily Average	40.16	43.84	42.58	34.39	39.97	26.90	36.26	33.06	37.84	34.55	37.71	**NA**	**37.02**	**4.56**
Total Tonnes	437392	381153	419021	470081	469786	441166	412099	400981	399343	336615	395169	**4562806**	**414800.55**	**37380.60**
Tonnes/CM/Shift	1071.88	1058.49	1126.22	1205.15	1262.66	1185.74	1163.92	1132.52	985.81	1019.95	1062.11	**NA**	**1115.86**	**80.53**
Tractor Breakdowns (14 Tractors)	14	18	17	16	23	14	17	10	24	22	19	**194**	**17.636**	**4.029**
MTBF (14 Tractors)	737.34	739.14	710.48	519.41	469.54	257.50	870.89	861.12	471.12	419.65	236.92	**NA**	**572.10**	**214.31**
MTTR (14 Tractors)	15.57	31.25	25.26	7.97	24.7303	37.11	20.30	14.73	35.52	13.41	9.80	**NA**	**21.43**	**9.67**
Tractor Breakdowns	28	40	40	34	36	38	47	27	41	47	31	**409**	**37.18**	**6.48**

Table E.2 shows the simulation output over the 11 month period from 01 July 2020 up to 31 May 2021.

Table E.2: Simulation monthly output for 01 July 2020 up to 31 May 2021

	Jul-20		Aug-20		Sep-20		Oct-20		Nov-20		Dec-20		Jan-21		Feb-21		Mar-21		Apr-21		May-21	
Support Service	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
Oil Deliveries (S68 and 320)	29.66	3.16	28.7	3.16	30.86	4.09	30.90	3.59	26.84	3.57	30.98	3.62	29.94	3.75	26.56	3.35	29.34	3.25	30.84	3.56	28.08	3.87
Production Material Requests	35.96	4.04	32.5	3.53	34.20	3.89	34.82	3.65	31.10	4.06	34.44	4.64	34.46	4.39	30.10	3.30	33.46	4.68	32.32	3.63	32.00	3.66
Sub Deliveries	104.88	12.94	105.28	9.93	103.46	11.35	112.38	12.76	98.86	12.73	112.82	11.24	106.64	14.95	95.76	12.29	105.12	12.78	107.00	12.98	107.16	9.66
Cage Trips	1099.36	41.88	1110	36.92	1092.60	42.55	1138.13	43.91	1060.92	35.45	1140.23	43.64	1119.87	37.60	1005.53	38.40	1111.79	37.67	1095.03	33.26	1105.97	37.51
Cage Trips Daily Average	36.12	1.21	35.91179	1.37	35.86	1.21	36.50	1.11	35.68	1.21	36.55	1.35	35.71	1.11	36.32	1.39	36.64	1.37	35.29	1.13	36.69	1.34
Total Tonnes	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tonnes/CM/Shift	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tractor Breakdowns (14 Tractors)	22.00	4.63	19.22	5.81	18.76	5.63	18.58	5.41	15.98	4.65	18.44	5.47	18.24	4.87	17.26	5.37	18.34	4.84	19.10	4.44	19.22	5.47
MTBF (14 Tractors)	496.33	112.89	607.8489	236.27	586.63	172.90	613.63	197.50	698.11	253.43	621.51	201.35	616.85	180.62	610.40	238.33	612.93	181.35	565.36	171.29	600.28	232.56
MTTR (14 Tractors)	19.94	6.88	21.07534	11.49	17.78	8.43	23.10	11.52	21.11	12.26	20.15	8.80	20.43	9.89	21.73	9.22	20.37	7.51	21.24	12.90	23.93	14.81

APPENDIX F Equivalence Tests

The equivalence tests for the different tractor support services and model output are shown below.

Test

Null hypothesis: Difference ≤ -33.6 or Difference ≥ 33.6
Alternative hypothesis: -33.6 < Difference < 33.6
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -33.6	49	10.680	0.000
Difference ≥ 33.6	49	-24.675	0.000

The greater of the two P-Values is 0.000. Can claim equivalence.

Figure F.1: Equivalence test for oil delivery

Test

Null hypothesis: Difference ≤ -38.7 or Difference ≥ 38.7
Alternative hypothesis: -38.7 < Difference < 38.7
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -38.7	49	10.548	0.000
Difference ≥ 38.7	49	-37.309	0.000

The greater of the two P-Values is 0.000. Can claim equivalence.

Figure F.2: Equivalence test for production material delivery

Test

Null hypothesis: Difference ≤ -126.6 or Difference ≥ 126.6
Alternative hypothesis: -126.6 < Difference < 126.6
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -126.6	49	3.4508	0.001
Difference ≥ 126.6	49	-40.324	0.000

The greater of the two P-Values is 0.001. Can claim equivalence.

Figure F.3: Equivalence test for sub-assembly delivery

Test

Null hypothesis: Difference ≤ -1262.5 or Difference ≥ 1262.5
Alternative hypothesis: -1262.5 < Difference < 1262.5
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -1262.5	49	15.020	0.000
Difference ≥ 1262.5	49	-37.881	0.000

The greater of the two P-Values is 0.000. Can claim equivalence.

Figure F.4: Equivalence test for the number of cage trips

Test

Null hypothesis: Difference ≤ -456281 or Difference ≥ 456281
Alternative hypothesis: -456281 < Difference < 456281
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -456281	49	12.878	0.000
Difference ≥ 456281	49	-148.66	0.000

The greater of the two P-Values is 0.000. Can claim equivalence.

Figure F.5: Equivalence test for total tonnes

Test

Null hypothesis: Difference ≤ -111.59 or Difference ≥ 111.59
Alternative hypothesis: -111.59 < Difference < 111.59
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -111.59	49	29.963	0.000
Difference ≥ 111.59	49	-120.24	0.000

The greater of the two P-Values is 0.000. Can claim equivalence.

Figure F.6: Equivalence test for tonnes/CM/shift

Test

Null hypothesis: Difference ≤ -19.4 or Difference ≥ 19.4
Alternative hypothesis: -19.4 < Difference < 19.4
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -19.4	49	13.751	0.000
Difference ≥ 19.4	49	-3.7192	0.000

The greater of the two P-Values is 0.000. Can claim equivalence.

Figure F.7: Equivalence test for the number of tractor breakdowns

Test

Null hypothesis: Difference ≤ -57.210 or Difference ≥ 57.210
Alternative hypothesis: -57.210 < Difference < 57.210
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -57.210	49	6.2572	0.000
Difference ≥ 57.210	49	-13.094	0.000

The greater of the two P-Values is 0.000. Can claim equivalence.

Figure F.8: Equivalence test for the MTBF

Test

Null hypothesis: Difference ≤ -2.1426 or Difference ≥ 2.1426
Alternative hypothesis: -2.1426 < Difference < 2.1426
α level: 0.05

Null Hypothesis	DF	T-Value	P-Value
Difference ≤ -2.1426	49	2.8296	0.003
Difference ≥ 2.1426	49	-5.4494	0.000

The greater of the two P-Values is 0.003. Can claim equivalence.

Figure F.9: Equivalence test for the MTTR