THE DEVELOPMENT OF A DISCRETE-EVENT BASED SIMULATION MODEL TO IMPROVE LARGE DIAMETER STEEL WATER PIPELINE CONSTRUCTION PROCESSES

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EXECUTIVE SUMMARY

Water pipelines is a convenient way of transporting water over long distances. Construction processes of water pipelines consist of a series of sub-processes with tasks that must be executed in a certain way to complete a project work item. The tasks within these sub-processes include, but are not limited to, people and resources, and the tasks time is influenced by safety - and environmental factors and management restrictions. Difficulties are found when planning and implementing such a complex construction process.

The main objective of the project was to develop a simulation model to identify inefficient and constraining activities and find improvements opportunities for the tie-in process within a water pipeline construction process, since the importance of timely execution there-of. The tie-in process consists out three major consecutive tasks, and consists of two crews. The first task is welding the two pipe-ends together and is executed by Crew 1. The next two tasks are coating the outside of the pipe for protection and then applying internal lining for protection. The latter two tasks are both executed by Crew 2.

A discrete event simulation model was developed to incorporate all the relevant input data, experimental factors, as well as outputs. The model was used to simulate an as-is case and comparing the results to known results of a completed project. The model simulated a 1.4 joints/day, which compares well with the actual recorded 1.2 joints per day. The simulation results were scrutinised to identify the constraints in the process. It was found that the idling time of the Crew 1, caused by it waiting for the Crew 2 to access the pipe, represented the primary constraint. The model was then used to experiment to find improvement opportunities for this constraint. The introduction on access holes in the pipe, which decouples the two crews, was modelled. This resulted in a less than expected improvement, due to the Crew 1 still idling when reaching the Management Exposure Restriction m. To resolve this, the production of Crew 2 had to be improved by allowing for simultaneous execution of lining and coating (effectively adding another Crew 2), which then resulted in a balanced process where idling of Crew 1 (the chosen constraint), is minimised. The model simulated a production rate of 2.1 joints/day and a cost R17.6m (for 4,000m). The rate represents an improvement of 50% on the as-is case production rate. It is also concluded that the model may be used as a management tool, which can aid Aurecon in the planning and control of future projects.

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CHAPTER 1

1 <u>INTRODUCTION</u>

Water pipelines is a convenient way of transporting water over long distances. Construction processes of water pipelines consist of a series of sub-processes with tasks that must be executed in a certain way to complete a project work item. The tasks within these sub-processes include, but are not limited to, people and resources, and the tasks time is influenced by safety - and environmental factors. Difficulties are found when planning and implementing such a complex construction process. There is a need to implement industrial engineering principles to better understand the behaviour of these complex construction processes and identifying improvement opportunities. For the purpose of this project, a company called Aurecon was chosen.

1.1 PROBLEM BACKGROUND

Aurecon is an engineering and infrastructure advisory company. Aurecon provides services on projects for numerous markets such as health, energy, water and construction, nationally and internationally. Aurecon has many diverse areas of expertise. One of these areas is Water Resource Management, where experienced engineers and scientists provide advice and skills to clients on water resource projects. The Water Resource Management division encounters water transfer system projects, where the construction of large diameter steel water pipelines is required. The large diameters ranges between 660mm and 1800mm depending on external factors such as the soil , altitude and incline of the area of installation (Aurecon, 2017).

The construction of large diameter steel water pipelines is recognised as being similar to an assembly line, with different teams performing different tasks. As teams complete their tasks, another team moves in to complete the next phase of the construction, making these tasks interdependent. Contrary to manufacturing processes, where the production environment is structured and enclosed in close proximity i.e. making organization easier, construction projects occur in an unstructured environment that is spread out i.e. making it difficult to organize. Complex resources, work dynamics, ambient factors (such as weather hold-ups) and other factors such as safety accidents and worker skill levels, cause variabilities. These variabilities cause time, cost and quality outcomes to be unpredictable and complicate planning.

The impact of having unpredictable time, cost and quality outcomes during construction processes is massive monetary losses for contractors involved and, in some worst cases, bankruptcy. Time hold-ups causes teams to inefficiently complete their parts, which creates errors that might threaten the final pipeline's structural integrity, for which the engineers of Aurecon are liable. Premature failures to the pipeline then also create a water deficiency in the community.

Defining what uncertainties exist, where they exist and how large they are, is the stepping stone towards designing a process that is least hindered by them. A simulation model can study the relationships between entities and their environment. It can assist in deciding what structural changes to the construction process can be made to improve it.

Furthermore, the model is reusable for future work because alternative scenarios and ideas can be implemented to the specific process within the model without disturbing the working environment.

1.2   PROBLEM STATEMENT

Every water pipeline construction process is unique due to factors such as its location and length of pipeline, but the basic sequence of tasks stays the same. The typical phases involved in the whole construction process is depicted in Figure 1 below.
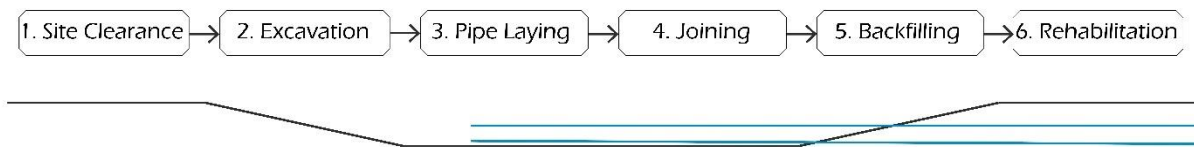
Figure 1: Water pipeline construction process

The process starts by making a right-of-way for the pipelines (1), i.e. by clearing the site so the construction equipment can operate safely. Next, ground is removed, and a trench is dug to a specified depth for pipe placement (2). After the pipes are delivered to the correct location, the pipes are lowered into the ditch (3). The pipe ends are joined by welding and protected against corrosion (4). The trench is then backfilled with ground (5) and the area is restored as closely as possible to its original pre-construction conditions (6). Various quality controls are executed within each of these steps.

Aurecon was involved in a two-year project called 'Mokolo Crocodile River Augmentation Project' which finished in 2014. They were required to construct a 46 km water pipeline to meet the growing demand for power generation, mining activities and domestic use in the Lephalale area (Aurecon, 2017). The project was delivered 15-weeks later to what was scheduled. During the execution of this project Aurecon documented a progress report making use of time studies on the completed part of the pipeline at that point. It was concluded in that progress report that the joining phase (number 4 in Figure 1 was the potential cause of the lag.

Aurecon suggested that an optimal daily production rate would be 3 joints/day. However, the progress report stipulates that the joining phase had a daily production rate of 1.17 joints/day.
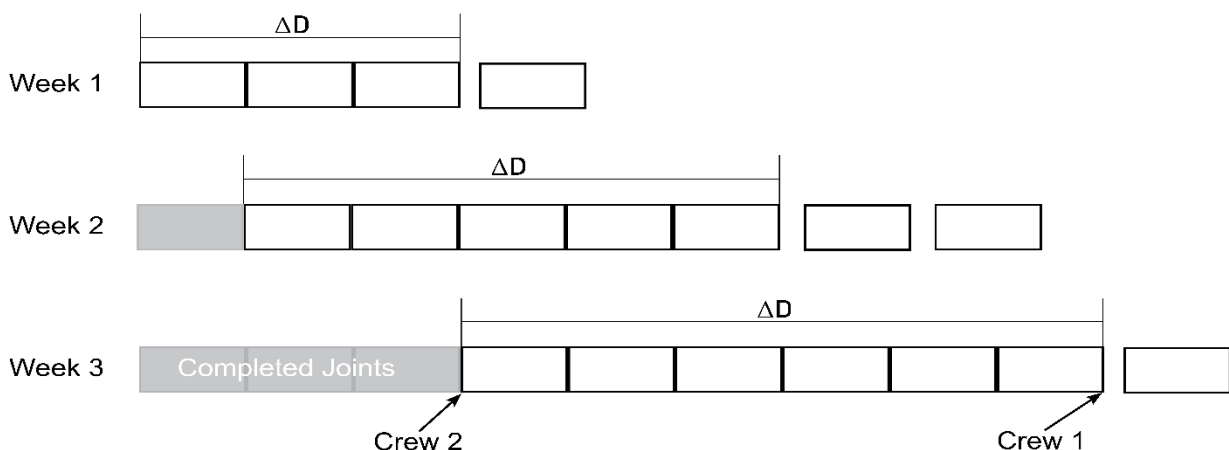
Figure 2: Visual representation of the crew dynamics

A joint is the output of the joining phase. The joining phases consists out three major consecutive tasks, and the joining team consists of two crews. The first task is welding the two pipe-ends together and is executed by Crew 1. The next two tasks are coating the outside of the pipe for protection and then applying internal lining for protection. The latter two tasks are both executed by Crew 2.

The progress report also encapsulated the dynamics and/or interactions between these crews. This can be used to understand the production rate outcome. Figure 2 illustrates a visual representation of the crew dynamics. As time progresses ΔD (which is the difference in pipeline length between the progress of Crew 1 and the progress of Crew 2) changes. Figure 3 shows ΔD over the duration of the project up until the progress report was compiled.
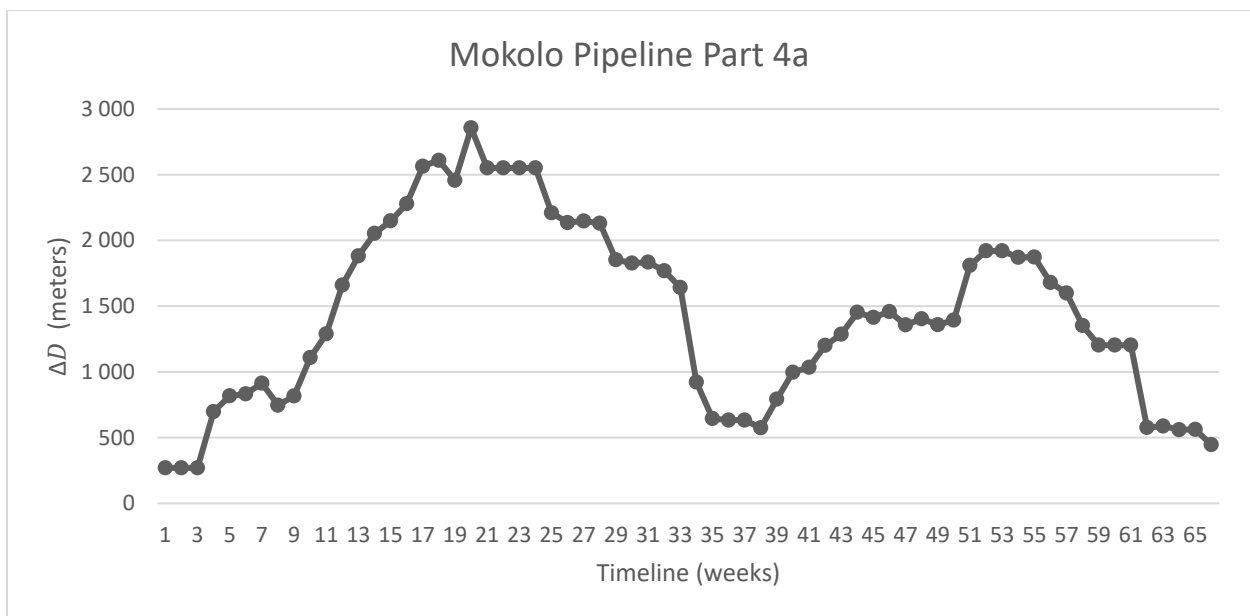
Figure 3: Difference in crew progress rate

The first thing to notice about Figure 3 is the graph conforms to a cyclic pattern. The gradual increase up to week 20 and in between week 39 and 53 shows how ΔD grows. This is due to the progress rate of Crew 2 being lower than that of Crew 1 or idling of Crew 2. The declines are due to Crew 1's progress being slower than Crew 2 or Crew 1 idling. Any idling is a waste of resources.

The second thing to notice is that the peaks of the cycles are high. At the peaks "Pipe fleeing" is proven. "Pipe fleeing" can informally be defined as the pipe "running away". Pipe fleeing is unwanted because long distances of pipelines can be exposed to ambient factors, such as rain and high temperatures. Rain can form a dam under the exposed pipeline causing the pipe to float out of position and high temperatures causes thermal expansions on the pipes. Repairing this can delay the entire construction process.

Questions around why the process performs in this way are asked. Aurecon bemoans that this is due to several reasons/variabilities, such as:

I.   Weather hold-ups.
II.   The absents of skilful workers.

III.   The number of repairs.
IV.   Inaccessibility to the internal pipes due to it being in a confined space.
V.   Restrictions such as the maximum distance a member can climb into the pipe to complete the internal lining. In a pipe fleeing scenario this forces contractors to create temporary access holes for the crew members to access the internal pipes, which can damage the pipes.

It is clear from the aforementioned issues that several variabilities, encountered in the joining process, effects the outcome of the entire construction process and results in monetary losses to Aurecon and the contractors involved. The scope of this project will be on the Joining process. From now the "joining process" will be referred to as the "tie-in process" to avoid confusion from some other known joining processes that happen outside of the trench (hole dug in the ground for the pipes).

This project focused on the tie-in process and the importance of timely execution there-of. This included an in-depth analysis of the behaviour of the tie-in process to improve productivity and provided Aurecon with a management tool to make more enlightened decisions for future processes.

Pipeline terrain can consist of either one of three different sections. Different construction methods are used for each (Zahran and Nassar, 2013). These are:

- The special sections, such as the troublesome terrain areas and expert working areas.
- Crossings, such as river, wetlands and road crossings.
- Open cross-country, such as the standard terrain sections.

The focus of this project was limited to the basic open cross-country sections. Because the timely execution of the basic sections is even more so important.

1.3   RESEARCH DESIGN

Many models have been developed to determine optimality in different construction processes. In this project a discrete-event simulation model (DES) for the tie-in process of large diameter steel water pipelines was developed. The objective was to unfold inefficient and constraining activities and find improvements opportunities of the process. This tool can aid Aurecon in the management of the tie-in process in similar future project.

1.4   PROJECT APPROACH

The execution of this project is outlined in the following steps:

I.   Literature review conducted to explore and investigate the construction field and solutions, and to gain a better understanding of simulation studies.
II.   Information gathered to obtain a clear understanding of activities involved in the tie-in process.
III.   Conceptual model developed.
IV.   Computer model developed.
V.   Model validated.
VI.   Experiments done to gain a better understanding of the tie-in process and reveal improvement opportunities.
VII.   Implemented by handing the model over to Aurecon.
VIII. Concluded and recommendations made.

CHAPTER 2

2 LITERATURE REVIEW

In this chapter, existing case studies with similar problems to that of the present problem and their solutions were investigated. Different tools and techniques that can aid in this project were also investigated.

2.1 SIMULATION MODELLING

2.1.1 Simulation definition

Robinsons (2004) defines simulation in his book as '*experimentation with a simplified imitation of an operation system as it progresses through time, for the purpose of better understanding and/or improving that system*' (Robinson, 2004). The operations systems that he refers to consists of the interactions between elements of human active systems and designed physical systems, with specific functions such as manufacturing, transport, supply and service. Most commonly, computer software is used to develop simulation models. The modeller experiments by varying the inputs of the dynamic model to determine the effect over time. Acting as a 'what-if' analysis tool, the model can aid in informed decision-making.

2.1.2 Reasons to simulate

Most operations systems are subjected to variability, interconnections and complexity. Complexity can be caused by the size of the system in terms of components involved or complex due to the dynamic interconnections and feedback within the system. Variabilities are defined as the changing nature of the elements involved. Having a system that is subjected to one, or a compound, of the effect described above makes predictions of the performance of the system difficult. Simulation models can clearly represent the complex systems with variabilities and interconnections. As a result, simulation models can predict the performance of a system, and compare the effect of alternative system designs. (Robinson, 2004)

2.1.2.1 Advantages of simulation

Robinsons (2004) explains simulation benefits in three different ways(Robinson, 2004). Firstly, simulation models enable organisations to innovate with real and relevant systems. This is an advantage due to obvious reasons such as the reduction of time-consuming and costly disturbance in the work environments. The less obvious reason being able to control the conditions under which the experiment is executed.

Secondly, comparing to other models such as spreadsheets and mathematical programming. Simulation modelling not only generates a more appealing and visual display for uninformed persons to understand but accommodates variabilities and its effect. It is essential to appropriately account for variabilities when predicting the performance of a system. Thirdly, simulation is beneficial from a management perspective as it creates knowledge and understanding to aid in decision-making and is a powerful communication tool to other organisations and colleges (Robinson, 2004).

2.1.2.2 Disadvantages of simulation

Robinsons (2004) then goes on to explain the disadvantages of simulation modelling which includes the unavailability of data that simulation models require and expert skills and knowledge of the chosen software when developing the model (Robinson, 2004).

2.1.3 Simulation modelling approaches

There are two main approaches to simulation modelling of construction processes. Each of these approaches are explained in the following paragraphs.

2.1.3.1 Agent-based modelling and simulation (ABS)

According to Macal and North (2010) agent-based simulation (ABS) can be traced to application in numerous complex systems. It entails the modelling of agents. No universal agreement can be found on the definition of an agent; however, agents are considered to have certain essential characteristics that contribute to the distinctive features of ABS. To explain these features, first an understanding of the typical agent structure should be obtained, this structure is illustrated in Figure 4.

Neighbouring agents

AGENT

Atrributes (Static and dynamic)
Behaviour

Environment
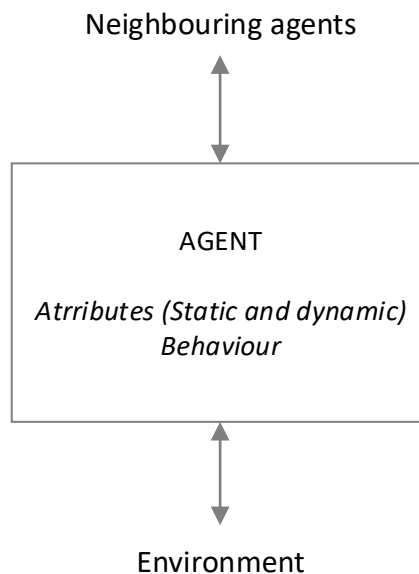
Figure 4: Typical agent structure

Agents consists of attributes that can be static such as their name or dynamic such as their memory or amount of resources they are endowed with. Agents entail certain behaviours which are usually described by simple rules and interaction with other agents. Agents have a relationship with their neighbouring agents, the relationship has a method of interaction basis which is defined by an underlying topology and connectedness. Topology includes a special grid and describes who transfers information to whom. Additionally, agents interact with their environment. The environment provides the spatial location and other situations such as infrastructure capacities.

The elements within the structure of an agent must be identified, modelled and programmed in order to develop an ABS model. Each run of the simulation has agents repeatedly execute their behaviours and interactions.

Having explained the structure of an agent, some features of agent-based modelling is discussed in the successive points.

- Agents can learn from its experiences and memory and adapt to their environment.
- Agents can self-organise by interaction with other agents that in turn influence their own attributes.
- Modelling agents exclusively, a systems behaviour can be observed by the effect of variety that exists among these agents' attributes and behaviours.

These features, when applying ABS modelling by means of agent-based modelling software, can not only gain perspective of a systems behaviour but results are intended to inform policies and decision making. (Macal and North, 2010)

2.1.3.2 Discrete-event modelling (DES)

In a Discrete-Event Simulation (DES) model time advances from one event to another. An event represents a significant change in the model. Entities and resources flow through a process portrayed by a logical sequence of steps. DES modelling software usually include pre-set elements to represent the logic, such as a seizing element, queue element, etc. The entities and resources are not able to interact with one another and do not exhibit adaptive behaviour. (Goh and Askar Ali, 2016).

DES models are commonly used in manufacturing industries, although lately service industries have also made use of it (Tako and Robinson, 2010). DES is the most traditional approach found in construction research (Goh and Askar Ali, 2016).

2.1.4 Steps in a simulation study

Figure 5 depicts an outline of a simulation study guided by Robinsons book on Simulations (Robinson, 2004). The boxes are the key deliverables:

- A conception model: A representation of the computer simulation model to be developed.
- A computer model: The simulation model developed on a computer.
- Solutions/Understanding: The results of the experimentation.
- Real world improvements: The implementation of the solution/understanding gained.

The arrows depict the processes that allows back and forth motion between the deliverables. The processes are discussed in the following paragraphs.
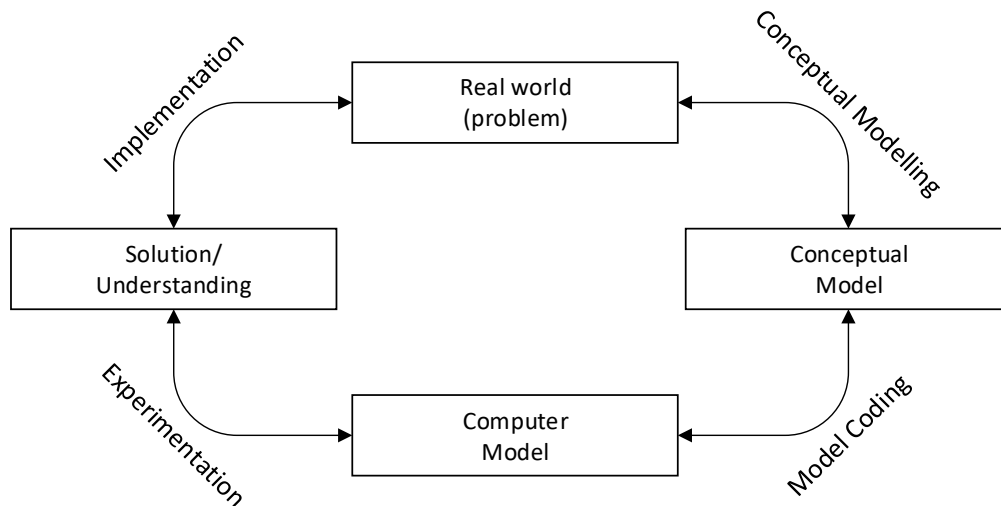
Figure 5: Simulation Studies: Key deliverables and processes (Source: (Robinson, 2004))

2.1.4.1 Conceptual modelling

A conceptual model is a non-software representation of the computer simulation model to be developed. It is important because it magnifies the success of meeting the objectives of a simulation study. Normally, conceptual model precedes the computer model development stage and sets the basis on which the computer simulation model is developed. However, as the simulation study progresses the problem situation and knowledge thereof change, with the simulation being the primary force to this change. The conceptual model and computer model should be live models with iterations existing between them.

Four basic requirements that should be kept in mind when designing a conceptual model have been identified by Robinsons (2004):

- Validity: Insight from the modellers perspective that the conceptual model is right for the given purpose.
- Credibility: Insight from the client's perspective that the conceptual model is right for the given purpose.
- Utility: Insight from both the modeller and client that the conceptual model will lead into a computer model that is useful for informed-decision making.
- Feasibility: Insight from both the modeller and client that the conceptual model can successfully result in a computer model.

A framework for the development of a conceptual model consists of:

I.   Developing an understanding of the problem situation, for example describing the operations of the real-world process.

II. Defining the modelling objectives. This includes asking questions such as "What does the client hope to accomplish?", "What level of performance is required?" and "What limitations must the client work with?"

III. Defining the required inputs and outputs. This can be defined as the experimental factors and the responses. Experimental factors are those factors that the client and modeller would alter to bring about the improvements, while responses are the outcomes desired to detect whether the objectives are achieved. Important to take into consideration when defining the responses is how it will be represented, for example numerically or graphical.

IV. Identifying the model content. This uses the experimental factors and responses to form the basis of what the model must include in order to accept the experimental factors and provide the responses. An example of this would be the components of the system and their interconnections. In this step assumptions are made and recorded to simplify the process.

2.1.4.2 Model coding

Model coding encompasses the conversion of the conceptual model into the computer model. Usually, coding can be defined as entering information into a computer, most likely into a simulation software package.

Robinsons (2004) advises to build a model structure before jumping into coding. A model structure outlines the logic of the simulation in software terms. This usually comprises of the variables, attributes and logic of the model depending on the software and model approach being used. To aid in model structuring, a prototype of a part of the system could be modelled in the software. This is advantageous because the user can rapidly alter coding approaches if need be. As mentioned in the conceptual modelling process, simulation studies entail iterations. This is true for the model structure as well.

After the model structure is designed, the development of the computer model itself consists of three vital actions. Firstly, developing the code in the simulation software. Secondly, verifying and white-box validating the model. Verification ensures that the model is true to the conceptual model, that is completed by the modeller alone. White-box validation ensures that the model is true to the real world, this involves others cognisant of the real-world processes. The third and final action is documenting the details of the model. These three actions can be completed in small steps to ensure more thorough results.

Robinsons (2004) recommend that modellers separate the general model input data, experimental factors and results when developing the software model. This is advantageous to users, because they can have access to the experimental factors and results without having to understand the details of the simulation code.

2.1.4.3 Experimentation

Once the model is developed, experiments are performed to obtain a better understanding of the real-world and discover improvements for the problem. Experiments are performed in simulation runs. In each run a cyclic process consisting of changing the experimental factors, inspecting the results and learning from the results is executed.

The experimental factors might be different to the factors identified in the conceptual modelling phase because the computer model might reveal different areas of concern. This change however is expected as a simulation study is iterative in nature.

Vital issues when performing the experiments are:
- Gaining satisfactorily accurate results.
- Execution a thorough search of possible solutions.
- Checking the robustness of the solutions.

2.1.4.4 Implementation

This process can be seen in three manners. First, the improvements found in the experimentation is put into practice. A second way of implementation is handing over the model to the client for further work. In this case the model's usefulness should be continuously controlled. The last interpretation of the implementation is where the model has led to knowledge and learning for the clients. A study can result in one or more of these implementation manners.

2.2 EXISTING CASE STUDIES

Research was done on the implementation of the simulation modelling tool on problems similar to this report.

2.2.1 Planning tool for oil and gas pipeline construction

The study completed by Zahran and Nassar (2013) looked at the challenges of complexity, repairing activities, external environmental influences, and different construction techniques involved in oil and gas pipeline construction and how they generate uncertain estimation of scheduling and cost. Focus was placed on resource allocation optimisation because massive delays to project durations comes from deficient use of resources.

To overcome this problem the paper presented computer simulation as a tool to assist contractors when planning for these pipeline projects because simulations can estimate the total duration and cost of projects and have the ability to utilize the resources. In order to model the pipeline construction process, a detailed sequence of activities involved in the process where collected, as well as the resources involved in each activity. The resources being a combination of people and machines.

These activities and resources related to the "spread technique" which is defined as the installation section of the construction process on open cross-country areas, excluding river - and road crossings and special sections. The computer simulation was developed with the data collected utilising a general-purpose simulation engine called EZStrobe, which is specifically designed for construction processes.

In the study a mock example of an oil and gas pipeline installation process was used to demonstrate the use of the simulation model. Arbitrary activity durations and costs where used. 36 different configurations of the resources where run, resulting in a scattered distribution as seen in Figure 6.

The total duration of the pipeline construction is portrayed on the x-axis, and the y-axis represents cost per 10meter pipe constructed. Each arrangement of different size teams and equipment are distributed on this graph. The least cost and least duration technique were used to reveal the best scenarios. Table 1 contains the configurations.
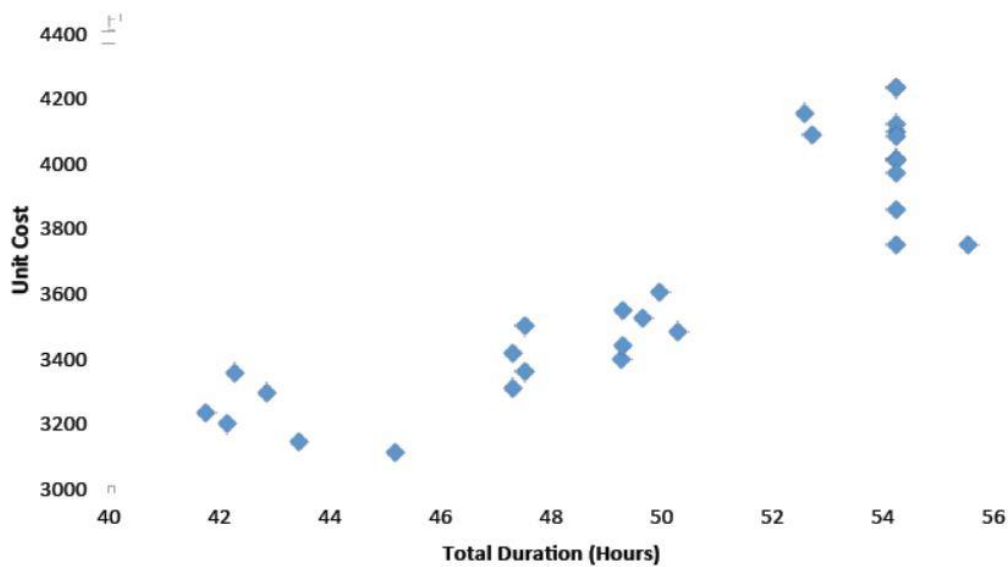
Figure 6: Results of the simulation model (Source:(Zahran and Nassar, 2013))

Table 1: Best scenario's results (Source:(Zahran and Nassar, 2013))

| | Scenario No. | Unit Cost ($/10m) | Total Duration (h) | Resource Configuration | | | | | | | | | | |
				GPS Team	Tail Hole Team	Survey Team	Loaders	Trucks1	Trucks2	Cranes1	Cranes2	Weld Team	Inspection Team	Excavators
The Least Cost	34	3104	45.2	2	4	6	4	7	7	1	6	4	2	5
The Least Duration	36	3224	41.76	2	4	6	4	9	9	1	6	4	2	6

The only difference to the least cost and least duration scenarios is the number of excavators. Contractors can now make an informed decision on which scenario to use. To conclude, the paper provided an overview of a simulation tool that can successfully assist contractors in planning for resource utilisation in pipeline construction processes (Zahran and Nassar, 2013).

2.2.2 Evaluation of different simulation models for earthmoving processes

The compendium compiled by Zankoul et al. (2015) states that in many construction processes the activities involved in the earthmoving sub-processes necessitates heavy equipment that are generally timeous and costly, making it the most expensive operation in construction processes. For this reason, it is important to properly manage the resources of the process.

According to their research construction industries are growing more competitive along with the need to continuously improve the construction performance. The paper had two purposes, namely to express and envision the earthmoving process to define the non-value activities and improve the efficiency of the process. Efficiency defined as achieving what is expected. This was done using simulation in a simulation engine called Anylogic 7.1. Secondly, two different types of simulation approaches were compared and the advantages and disadvantages of each in earthmoving processes was evaluated.

To model the process, data were gathered on the sequence and interaction of each activity. The operations in the scope of the paper existed out of soil cutting activities executed by excavator machines and soil filling activities executed by loader machines. Hauling of the soil done by trucks was also included. Data gathered on the daily output of these activities and the machine parameters where used as input to the models. A Discrete-event simulation (DES) approach and an Agent-based simulation (ABS) approach was used respectively. These approaches are defined in section 2.1.3 in the literature review of the present report.

An MS Excel file was designed to apt the user to change the quantity of soil that needs moving and dimension of each segment of earth. Making use of this excel file the models were then applied to an applicable case study of a potential wind-farm where the construction of road network between wind turbines is required.

An Edit-Box that changes the number of trucks available aided as the experimental factor as trucks are the critical resource in this process. Both model responses to the different number of trucks chosen for each run is represented as the total project duration. This is depicted in Table 2. The variation of the two models' duration for every number of trucks stay smaller that 1% except for one outlier of 1.15% that is negligible.

Figure 7: Average duration versus number of trucks (Source: (Zankoul et al., 2015)) shows a graph of the average project duration of the DES and ABS models for the number of trucks chosen. The graph reveals an exponential decline in total project duration as the number of trucks increase. The graph levels at the minimum duration of 500 hours and nine trucks. This implies that availing more trucks than nine will have a small impact on the duration of the project, making nine trucks the optimum number of trucks to minimise the project duration.

Although both models generated the same durations a comparison of the two models revealed the advantages and disadvantages that the modellers faced during development. The disadvantages found in the DES approach include the need of additional elements not related to model logic, which was not required in the ABS approach. These additional elements slow the simulation runs. More confusion can also be encountered with the DES approach as unfamiliar concepts can be difficult to understand by the average user while, ABS logic is quite easier to grasp. DES models have built-in block/elements that makes it easier to create, but this shortage for the ABS approach can be advantageous, since it creates increased flexibility for the modeller.

Table 2: DES and ABS model results (Source: (Zankoul et al., 2015))

Number of Trucks	Duration (hours)		Variation (%)
	DES	ABM	
1	4827	4790	0.77
2	2415	2395	0.83
3	1610	1597	0.84
4	1207	1198	0.75
5	966	958	0.87
6	805	799	0.81
7	690	685	0.75
8	604	599	0.79
9	538	533	0.92
10	486	480	1.15
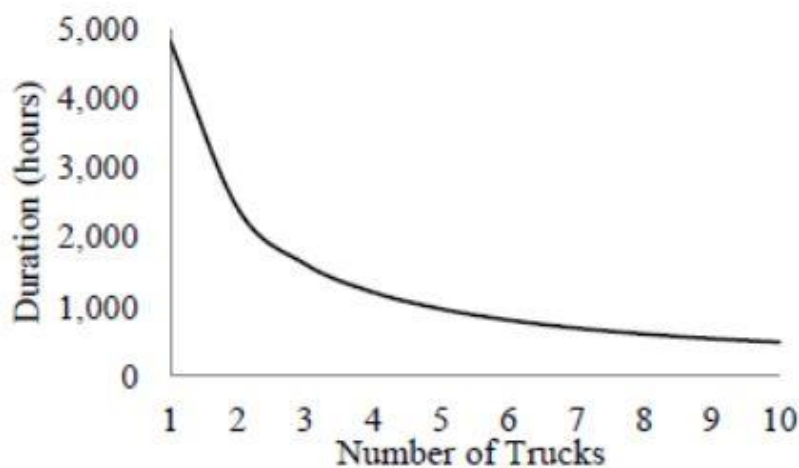
Figure 7: Average duration versus number of trucks (Source: (Zankoul et al., 2015))

The paper concludes that the use of model approach rest on the modellers preference and scenarios being modelled. It was suggested to create a multi-method simulation model to benefit from the advantages of both. Both models provided an improvement opportunity to shorten the duration of the process by using the most appropriate number of trucks (Zankoul et al., 2015).

2.2.3 Productivity improvements of onshore oil and gas pipeline tie-in joints executions

In the paper authored by Kuppusamy and Ramar (2011) a tie-in joint execution of an onshore oil and gas pipeline was modelled. The problems they faced was maintaining high-level productivity. This was due to low skill levels of workers, limited and confined work areas, sequence of activities executed and the work methods used.

To gain a better understanding of the process, it was modelled through simulations in a software called STROBOSCOPE. The model was applied to a live pipeline project in India. Probability distributions of durations and the cost of the activities involved where used as input. The model revealed that 82% of the total time was consumed by the removal of end cap, pipe cutting, edge preparations and fit up.

An alternate working sequence was designed for these activities. Twelve different scenarios were run for the existing sequence and for the alternative sequence. In each scenario the modellers had the option of changing the number of resources and joints to be completed. The percentage change in cost output of scenario k, where k=1, 2, 3, …, 12 and the first scenario and original configuration was weighted against each other.

Table 3 depicts these results. Negative percentages portray an increase in cost. The string of numbers represented in the 'Existing' and 'Alternate' columns are the different number of resources that the modellers had the option of changing. The two columns numbers differ for each scenario since the 'Alternate' column depicts an alternate sequence of the activities and therefore a different string order.

Table 3: Percentage of change in cost comparison (Source: (Kuppusamy and Ramar, 2011))

Scenario	Existing	Chance (%)	Alternate	Change (%)
1	1751932	0.00	1743040	0.50
2	1747372	0.30	1738480	0.80
3	1738708	0.80	1736200	0.90
4	1735516	0.90	1726852	1.40
5	1801261	-2.80	1792369	-2.30
6	1697860	3.10	1695352	3.20
7	1686460	3.70	1683724	3.90
8	1681444	4.00	1679164	4.20
9	948848	45.80	938132	46.50
10	1787809	-2.00	1785530	-1.90
11	1784389	-1.90	1313897	25
12	937221	46.50	935396	46.60

As evident in Table 3, simply following the alternative sequence for scenario 1 can generate a 0.5% decrease in cost. By utilizing the best scenarios which were 9 and 12, 46% can be saved in costs. This pose yet another example of a simulation model that empowered the users to improve a tie-joint sub-process that forms part of a pipeline construction process. Additionally, a tool to unfold the constraining activities is also represented in this case study (Kuppusamy and Ramar, 2011).

2.3   SUMMARY OF LITERATURE REVIEW

The aforementioned three case studies successfully applied simulation modelling in cases where problems and examples was similar to that of the present study.

In case study one the construction process of an oil and gas pipeline was improved by deciding on the optimal crew configuration though calculating cost and time trade-off. Noting that the sequence of activities and resources used in oil and gas pipeline construction are very similar to that in water pipeline construction, the case study serves as a justification for using the simulation modelling tool in the present project. The model proves to give the capacity to experiment with crew configurations as a possible improvement.

Case study two evaluated the DES and ABS approach on earthmoving processes and concluded that the best approach rests on the modeller's choice. Seeing, that the tie-in construction viewed in the present project consist of variabilities and an active construction process similar to earthmoving processes, both DES and ABS approaches can be used in these types. The DES approach was used as it was the modellers choice.

Case study three used simulation modelling to identify what time-consuming activities for improvements should be focused on. This also serves as justification of using simulation modelling in order to unfold the necessary time-consuming activities the present project can focus on.

Following the framework researched for simulation studies a discrete-event simulation model was developed on the chosen software. The simulation model as evident in the research and case studies can serve as a tool to meet the objectives of the present project. Reviewing that the objectives is to unfold constraints in the tie-in process, improve the process and aid Aurecon in future management decisions of similar projects.

CHAPTER 3

3 METHODOLOGY

This chapter consists of the conceptual model, numerical model and validation of the simulation model.

3.1 CONCEPTUAL MODEL

As explained in section 2.1.4 of the Literature Review, a conceptual model is a description of the computer simulation model to be developed. This section contains information gathered from Aurecon which aids in the development of the conceptual model guided by Robinson's (2004) framework and cognisant of the four requirements as discussed in section 2.1.4. The problem is fully explained in the problem statement and objectives are defined in the research design.

3.1.1 Information gathered

A logic flow diagram of a typical tie-in process was constructed through a structured focus group with five experienced engineers of Aurecon, specifically experienced and involved in one or more large diameter steel water pipeline construction projects. The Logic flow diagram was constructed using the standard symbols as explained in Figure 8 below.
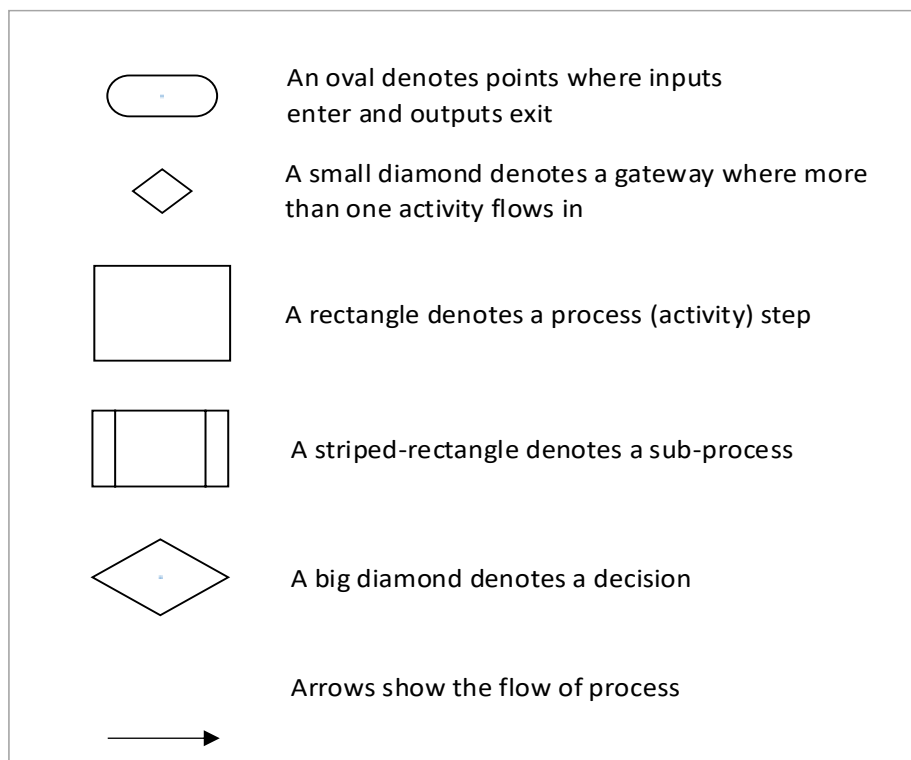
Figure 8: Standard flow diagram symbols

Figure 9 depicts the typical detailed steps of a tie-in process which is the result of the focus group brainstorming session. Figure 10 and Figure 11 unveils the sub-process visible in the diagram. Crew 1 and Crew 2 grouped in Figure 9 refers to the same crews discussed in the problem statement. The Special Crew (gold) is contracted for special tasks, of which repairing the joints that failed the graphical test is one of them.

Step 16 does not form part of the tie-in process, selected backfill forms part of phase 5 as seen in Figure 1. However, for reasons later discussed, an indication is given of when the first backfilling starts. The steps and flow of the diagram in Figure 9, Figure 10 and Figure 11 speaks for itself, however unfamiliar words and jargon is explained in the glossary in Table 4.
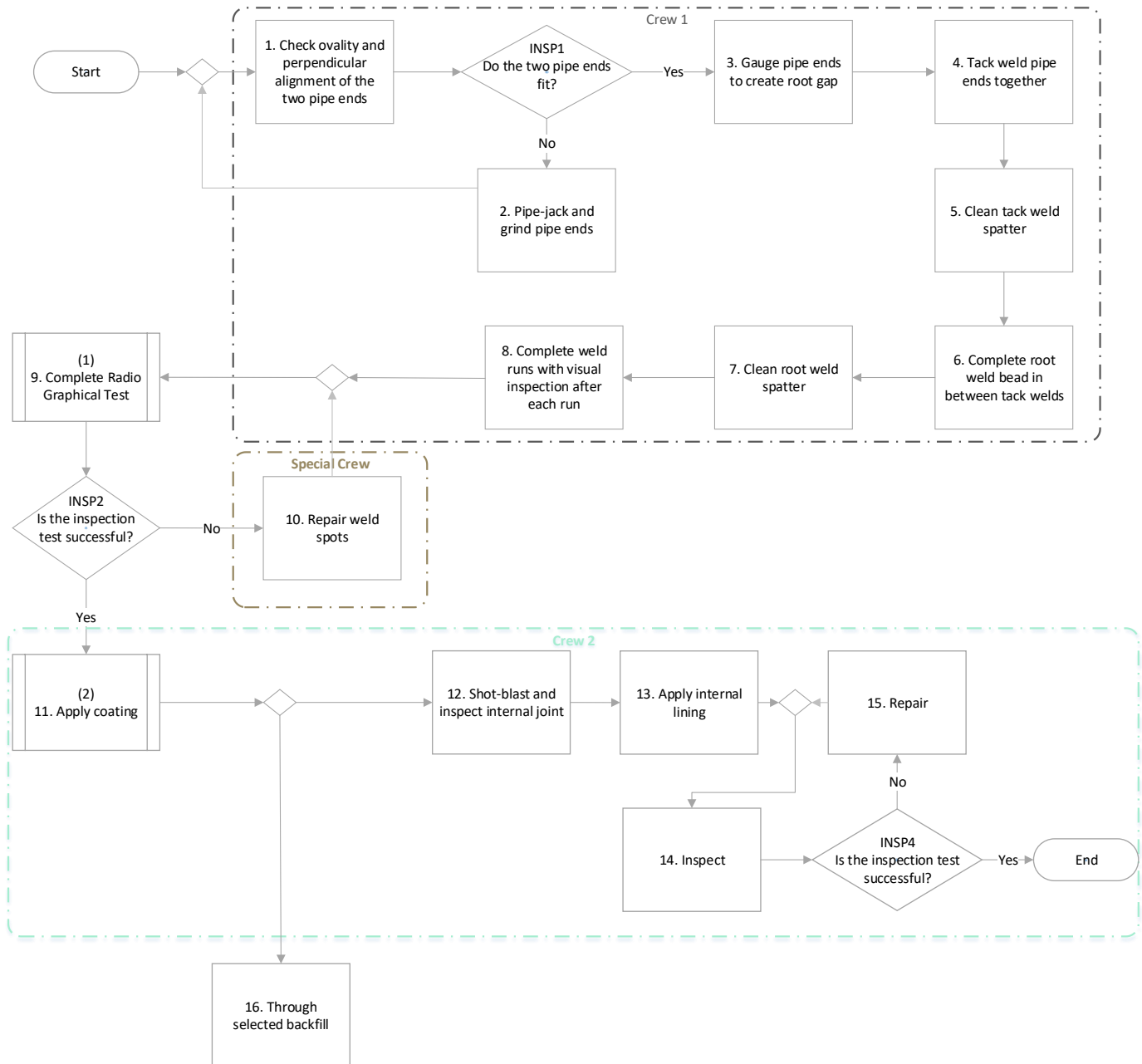
Figure 9: Tie-in Process
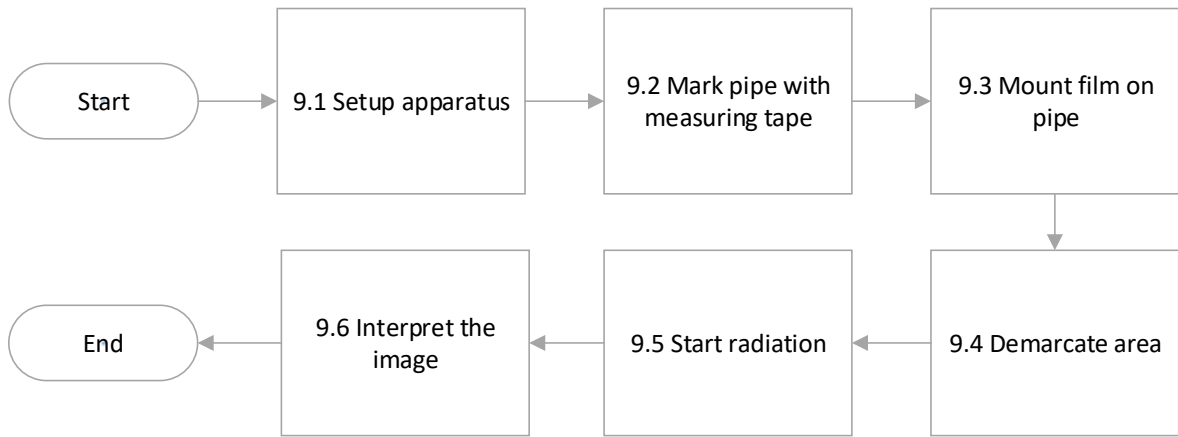
Figure 10: Radio Graphical Testing Sub-Process
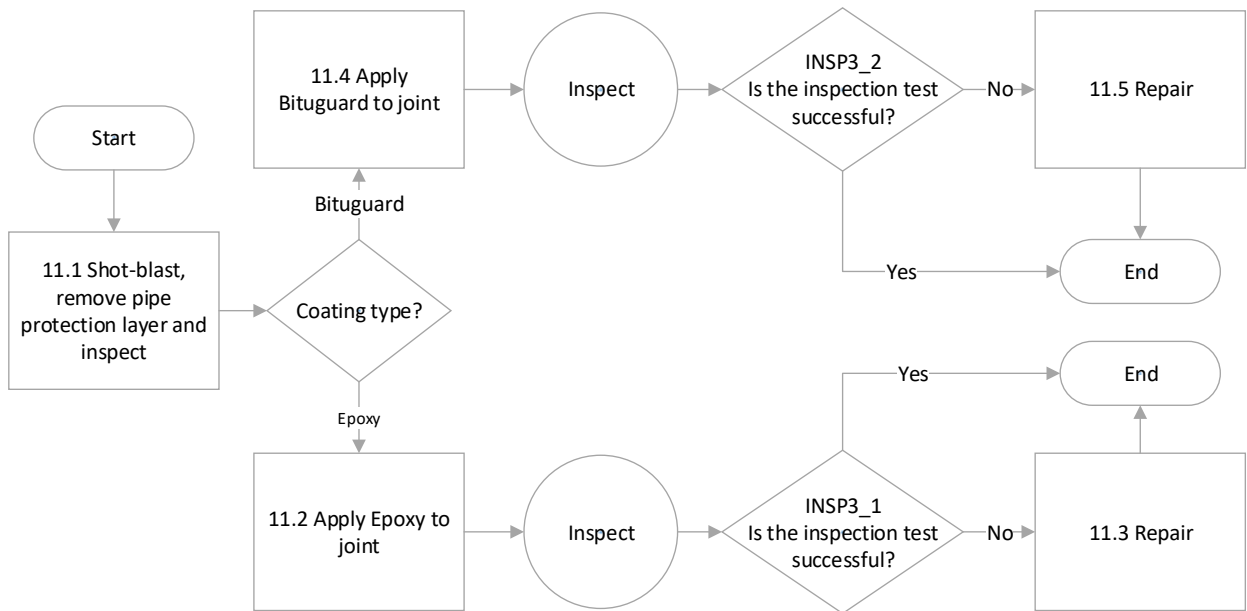
Figure 11: Pipe Coating Sub-Process

Table 4: Glossary for Pipeline Construction

Step no.	Words	Description
	Tie-in Process	
	INSP	Inspection
1	Ovality	Degree of deviation from perfect circularity
2	Pipe-jack	Deforming pipe with force
3	Root gap	Desired distance of pipe barrels end
4	Tack weld	Spots welded to fix pipes positions
6	Root weld bead	First deposited filler metal
13	Shot-blast	Cleaning metal by directing a high-speed stream of steel particles at it
14	Internal lining	Protection sheet for joint
16	Selected backfill	First layer of ground thrown to cover the pipeline
	Radio Graphical Testing Sub-Process	
9.1	Apparatus	Equipment designed to shoot x-ray waves
9.3	Film	Photographic material used in x-ray operations
9.4	Demarcate	Radiation boundaries setup in area
	Pipe Coating Sub-Process	
11.2	Epoxy	Glue material for wrap
11.4	Bituguard	Material that protects the pipe

3.1.2 Inputs and outputs

The outputs of the model to achieve the objectives are as follows:

- Cost (R/pipeline)
- Production rate (joints/day)
- Difference in pipe length between crews (m)
- Exposed pipeline length (m)
- Crew utilisation (%/crew)
- Total duration (days)

General input data

To deliver the outputs, the input parameters in Table 5 where identified.

Table 5: Input Parameters

Symbol	Assigned Value
Constants	
t_k	Baseline time distribution of step k (min)
D	Time Deviation (%)
f_q	Worker skill level at inspection q, where $q \in$ {INSP1, INSP2, INSP3_1, INSP3_2, INSP4} (% failure)
L	Pipeline length (m)
Non-constants	
A	Distance between access holes (m)
T	Length of a working day (min)
ℓ	Length of pipe (m)
d	Diameter of pipe (mm)
M	Safety Human Restriction (m)
m	Management Exposure Restriction (m)
h	Management Welding Restriction (min)
k_t	Coating type t, where $t \in$ {epoxy, bituguard}
c_j	Cost of Crew j, where $j \in$ {1,2} (R/day)
p_i	Cost of pipe with diameter i, where i {660 - 1800} (R/m)
K	Cost of T-shaped pipe (R/pipe)
r	Cost of a repair (R/failed joint)

Experimental factors

From the general input data, the possible experimental factors are as follows:

- Worker skill levels
- Distance between access holes
- Coating types
- Number of Crew 2's

3.1.3 Assumptions and limitations

In this section all the assumptions and limitations of the model is discussed.

Assumptions

The following assumptions were made:

- Crews were modelled as members only. It is assumed that materials, equipment, and transportation are in abundance. The effect of travelling time is also excluded.
- Selected backfill is not simulated as part of the process. It a different crew's responsibility, therefore, the assumption was that the backfill happens exactly after the coating and does not influence the lining that follows.
- It is assumed that the Radio graphical test is executed after hours by a 3rd party. Coating of a joint starts at the beginning of the next day once it passed the test.
- Repairs (step 10 of Figure 9) are executed by a special crew. They complete all special section within the entire construction process.

- Access holes are T-shaped pipes added at specified intervals on the pipeline, which gives Crew 2 alternative access to the inside of the pipe. When $A = 0$ there are no access holes (apart from the pipe-end), otherwise $A > 0$ represents the distance between the access holes.

Limitations

The following limits the computer model and explains some of the parameters used in Table 6.

- The only safety and health legislation that has an influence on the tie-in process is the maximum allowed distance between an access hole and a crew member working inside the pipe. This restricts the progress of the welding Crew. Hence, the parameter M (Safety Human Restriction) was included.

- A takes a value between 0 and M, this is to ensure adherence to the previous point.

- The welding procedure, as explained in Figure 9 (steps 1-8), consists of preparation, tack and root welding, followed by welding runs. Management realised that if a joint is only tack welded, and the rest of the procedure is suspended until the next day due to day time constraints, cracks can form in the night due to a drop in temperature. Therefore, management defined a restriction h that prohibits Crew 1 from starting the tack weld procedure (step 4), until the combination of the tack and root welding can be completed consecutively in the same day. Step 4 will only start if the time remaining in the day is larger than h.

- The Management Exposure Restriction m is defined as the maximum length (in meter) of exposed pipeline (before the ground is backfilled). Management implemented this restriction to eliminate the consequences of pipe fleeing and eliminate the negative influence of external factors such as rain and high temperatures.

3.1.4   Content

The component list in Table 6 explains the components of the system and the justification of the excluded components. These components are used to accept the input data and provide the output data.

Table 6: Component list of the tie-in process

| Component	Include/Exclude	Justification
Entities		
Members	Include	Influences the production rate
Equipment	Include	Assume no shortage of
Raw materials	Exclude	Assume no shortage of
Joints	Include	Influences the production rate
Processes		
Preparation	Include	Influences the production rate
Welding	Include	Influences the production rate
Coating	Include	Influences the production rate
Lining	Include	Influences the production rate
Inspecting	Include	Influences the production rate
Selected back filling	Exclude	Not a constraint
Pipe laying	Exclude	Not a constraint

3.2 COMPUTER MODEL

This section explains the last iteration of the computer model. An in-depth explanation of the model logic and mathematical formulation follows, making use of the conceptual model, information- and data gathered. Model validation is also tested in this section.

3.2.1 Modelling tool

The software called Anylogic 8.3.2 Personal Learning Addition was used to model the tie-in process. Due to modellers choice, Discrete-Event Simulation (DES) modelling approach was used.

3.2.2 Modelling logic

A schematic overview of the modelling logic is shown in Figure 12 below, followed by a clear explanation of the flow and the custom symbols used. Through-out the explanation the input parameter defined in Table 6 will be referred to.
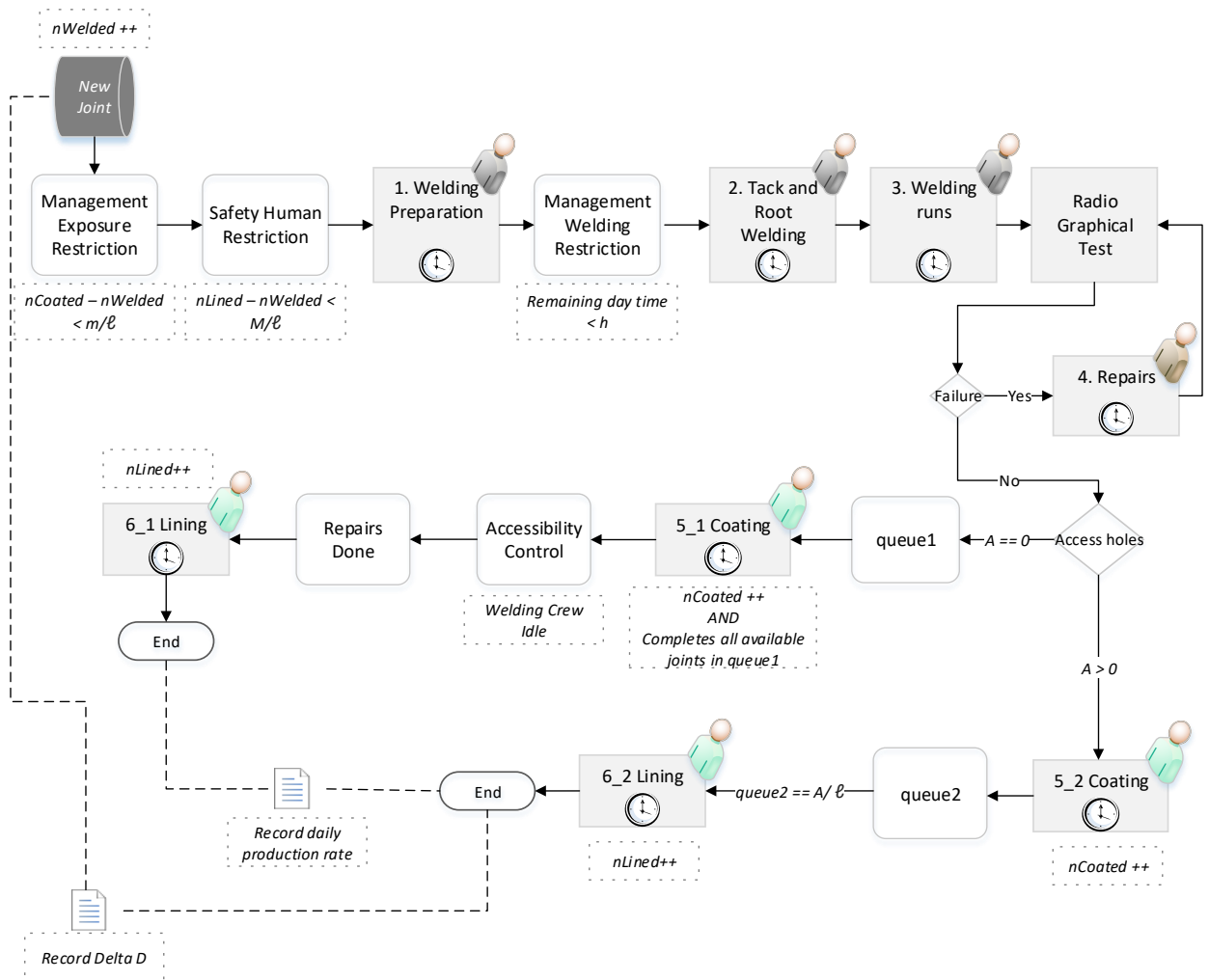
Figure 12: Schematic overview of model

Crews (represented by the person icon) were modelled as Resource Pools with a Member as an agent. Each Crew's logic is modelled separately to allow for parallel execution and Crew 2 may have more than one Member. Tasks, represented by the greyed-out rectangles, consist of the steps explained in detail in Figure 9 and are modelled as Delays with time distributions t_k calculated by the function Set_Times shown below.

The pipeline is divided into a Collection of joints. The size of the Collection is determined by L, the pipeline length. Joints are the entities that flow through the logic of the model. The model starts by sourcing an available joint and incrementing the Variable called nWelded, thus keeping count of number of joints in the process. Before entering Task 1, the model checks the Management Exposure Restriction. If the length of the exposed pipeline (number of joints in between this restriction point and Task 5_1 or Task 5_2 multiplied by ℓ) exceeds m, the joint will be held (delaying the welding progress) until the enough joints are coated and the restriction no longer applies. If the restriction does not trigger a hold, the joint will move to the Safety Human Restriction.

The Safety Human Restriction is only activated when there are no access holes ($A = 0$), in the case of access holes being used ($A > 0$) the joint will immediately move on to Task 1, because A is less than M. When this restriction is activated the model checks whether the length of the downstream joints at Task 6_1 or Task 6_2 is greater than M. The joint will be held until this restriction no longer applies. The joint then moves on to Task 1 where Crew 1 (grey shirts) is seized.

After the completion of Task 1, the Management Welding Restriction is checked using the time remaining in the day. If the remaining time is less than h, the joint will be held until the start of the next day. Otherwise, the joint passes through Task 2 and 3. At the end of these tasks a new joint is sourced, and Crew 1 starts with the new joints.

The Radio Graphical test occurs after hours by a 3rd party, therefore the joints are held until then. The model will randomly decide whether the joint passes or not based on the failure probability f_{INSP1}. If failed, the joint gets repaired (Task 4) and sent through the same testing procedure. Upon entering Task 4 the Special Crew (brown shirts) is seized.

If the joint does not fail, it enters a splitting point. Here, the model selects a path for the joint to follow depending on whether access holes are used or not. If $A = 0$, the joint will enter queue1 followed by Task 5_1, where Crew 2 (green shirts) is seized. Queue1 will be emptied before the joints can move on to Accessibility Control, which means that all available joints are first coated by the type of coating chosen through parameter k_t. Joints passing Task 5_1 will be counted in Variable nCoated.

The Accessibility Control ensures that Crew 1 idles, while Crew 2 climbs into the pipe at the opening where the Crew 1 must work. When Crew 1 idles the joint moves on to Repairs Done. The model checks whether the joint succeeds a joint that may have failed at Task 4. All joints succeeding a failed joint will not be lined by Crew 2 until the repair has been done and the joint has caught up to this point. This is to ensure that the joints that Crew 2 lines are consecutive. Only then the joints will pass through Task 6_1, where they will be counted in Variable nLined and sunk.

However, if $A > 0$ the joints will enter Task 5_2, with the same delay time as Task 5_1. The joint will then wait in queue2 until the length of pipeline in queue2 equals A. The joints will then be lined in Task 6_2 and sunk.

3.2.2.1 Output calculations

As seen in Figure 12 the Daily production rate is recorded after Task6_1 or Task6_2 is completed. The Difference in pipeline length between crews are recoded using the counted Variables nLined and nWelded. Making use of functions in Anylogic the resource utilisation by Crew 1 and Crew 2 is recorded.

The T-pipe dimensions and form can be seen in Figure 13. The use of T-pipes will have an effect on the output of the model since L, the length of the pipeline stays constant, but the number of joints that has to be completed changes.
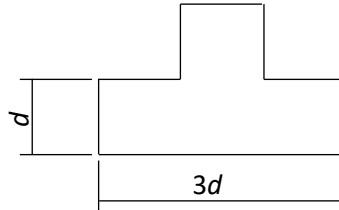
Figure 13: T-pipe

In the case of $A > 0$ the model calculates the size of the Collection of joints available according to Equation 1.

$$\text{Available Joints} = \frac{L}{A} + \frac{L - \left(\frac{L}{A} \cdot \frac{3 \cdot d}{1000}\right)}{\ell} \tag{1}$$

In the case of $A = 0$ the mode calculates the size of the Collection of joints available according to Equation 2.

$$\text{Available Joints} = \frac{L}{\ell} \tag{2}$$

The durations of completing the available joints by Crew 1 and Crew 2 are recorded as *Crew1Days* and *Crew2Days*, respectively. The total duration is recorded as the maximum of these two durations. The model counts the number of repairs by a Variable *Repairs.*

The Total cost of the pipeline L is then calculated in 1 of 3 different cases.

Case 1, where $A = 0$ Equation 3 is used:

$$\text{Total Cost} = c_1 \cdot Crew1Days + c_2.Crew2Days + p_i.L + r \cdot Repairs \tag{3}$$

Case 2, where $A > 0$ and only one Crew 2 Equation 4 is used:

$$\text{Total Cost} = c_1 \cdot Crew1Days + c_2 \cdot Crew2Days + p_i \cdot L + r \cdot Repairs + K\left(\frac{3 \cdot d}{1000}\right)\left(\frac{L}{A} - 1\right) -$$
$$p_i\left(\frac{L}{A} - 1\right)\left(\frac{\ell}{\frac{3 \cdot d}{1000}}\right) \tag{4}$$

Case 3, where $A > 0$ and two Crew 2's Equation 5 is used:

$$\text{Total Cost} = c_1 \cdot Crew1Days + 2 \cdot c_2 \cdot Crew2Days + p_i \cdot L + r \cdot Repairs + K\left(\frac{3 \cdot d}{1000}\right)\left(\frac{L}{A} - 1\right) -$$
$$p_i\left(\frac{L}{A} - 1\right)\left(\frac{\ell}{\frac{3 \cdot d}{1000}}\right) \tag{5}$$

3.2.2.2 Delay time calculation

During the focus group discussion, execution times relative to the diameter of the pipe was estimated. It was stated that the times of the steps are linearly proportional to the range of large diameters d, since diameter is directly proportional to circumference. Table 7 contains the data gathered on the steps defined in Figure 9 and Figure 11.

Table 7: Data gathered on the tie-in process steps

| Steps | Time (min/joint) | | Failure rate (%) |
| | Diameter(m) | | |
	0.66	1.8	
1	10	30	
2	120	240	10
3	10	30	
4	2	6	
5	5	15	
6	8	22	
7	10	30	
8	60	120	
9	*End of day*		
10	60	240	3
11.1	20	60	
11.2	90	180	
11.3	60	120	5
11.4	45	90	
11.5	30	60	8
12	30	60	
13	30	60	
14	5	10	5
15	32	88	

According to Aurecon each step time is triangular distributed, with a minimum and maximum of 20% deviation D. The simulation model uses the function bellow called Set_Times to calculate each step delay distribution (parameter t_k). Table 7 also shows the failure rates in percentages used for parameter f_q.

```
function Set_Times (d,D) {
//List_660 and List_1800 contains the times seen in table 7
for (int i = 0; i < List_660.size(); i++) {
//List_tk is created to store the distribution for the relevant steps
        List_tk = []
        Mean = (List_1800.get(i) – List_660.get(i))/(1800-660);
        Constant = List_660.get(i) – Mean*660;
        Mode = Mean*d + Constant;
        Min = Mode – Mode*D;
        Max = Mode + Mode*D;
        List_tk.add(triangular(Min, Mode, Max));
}
return (List_tk)
}
```

The Management Welding Restriction h is calculated as seen in Equation 6.

$$h = t_4 + t_5 + t_6 + t_7 \tag{6}$$

3.2.3   Input parameter details

Table 8 contains values gathered from the case study 'Mokolo Crocodile River Augmentation Project' referred to in the problem statement. Failure and cost values was estimated by the engineers of Aurecon at the same focus group meeting where the sequence and crew allocation information of the tie-in process was gathered. The pipeline length L value was chosen smaller than the real pipeline constructed in Mokolo boost simulation running speed. However, this action is justified in the following section called Runs and convergence. The simulation model with the values used in Table 8 will from now on be referred to as the as-is model.

Table 8: Mokolo input parameter values

Symbol	Value
D	20%
f_{INSP1}	10%
f_{INSP2}	10%
f_{INSP3_1}	5%
f_{INSP3_2}	2%
f_{INSP4}	5%
L	200 joints
A	0 m
T	420 min
ℓ	20 m
D	1100 mm
M	500 m
m	300 m
k_t	Epoxy
c_1	R 34 400
c_2	R 34 400
p_{1100}	R 3 000
K	R 47 000
r	R 1 400

3.2.4 Runs and convergence

The as-is model was run 20 times. The number of runs was chosen as a rule of thumb to analyse the effect of the length of the pipeline used on the production rate. Figure 14 exhibits this result.
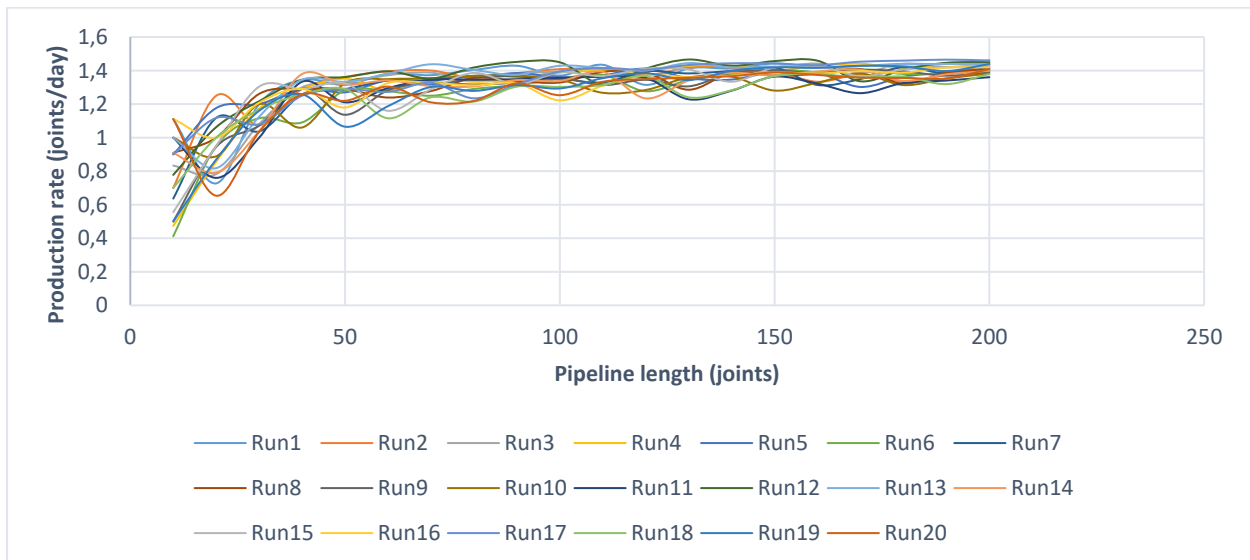
Figure 14: Daily production rate of varying pipeline lengths

From this figure two conclusions can be made. Firstly, at 200 joints the daily production rate already converges to roughly 1.4 joints/day. This means, running the model with pipelines longer than 200 joints will have only a small effect on the daily production rate. Modelling with only 200 joints of pipeline instead of the real length greatly improves the simulation modelling speed capacity. Secondly, the convergence

represents a steady state that forms after 20 runs. Figure 14 serves as a graphical method, that justifies that at 20 replications a point is reached where the line becomes flat. Performing more replications and longer pipeline lengths will only give a marginal increase in the estimated production. All further analysis and conclusions drawn on the outputs of the model was therefore performed with 20 runs and *L* remained constants on 200 joints.

3.3 MODEL VALIDATION

This section contains the model validation. Validation means proving that the model for a specific accuracy of a purpose is incorrect. If this cannot be proven the model confidence to the client grows. Validation was performed by comparing the output to available real time case study values, getting experts of Aurecon's opinions on the output and completing a data validation on the estimates given by Aurecon.

3.3.1 Case study comparison

Two of the simulation model outputs was compared to the values available in the progress report referred to in the problem statement, namely the daily production rate and the crew progress rate difference.

Daily production rate

Aurecon's progress report calculated a daily production rate of 1.173 joints/day. After 20 runs the as-is model generated a bimodal distribution exhibited in Figure 15.
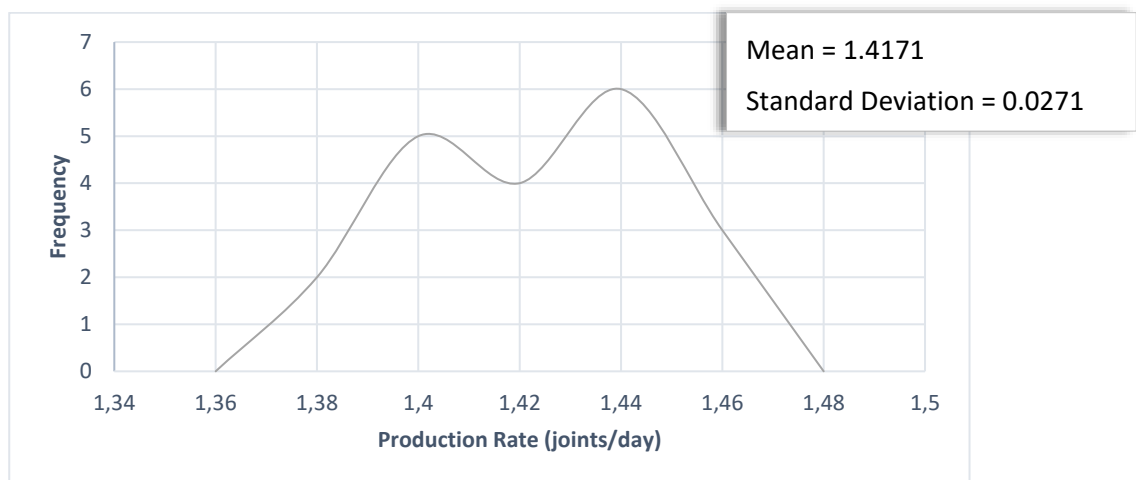
Figure 15: Daily production distribution of the as-is model

After comparing the mean of the distribution in Figure 15 with the progress report production rate a difference of 17.22% was obtained. The cause of this difference could be due to several factors such as the assumptions and limitations made, unknown influences on the tie-in process that was not clearly documented or inaccurate data. However, for the purpose of this project, which is to interpret the behaviour of the model, develop improvement opportunities on the interpretations and implement the model as a managing tool. This difference is specifically accurate.

Crew progress rate difference

Figure 16 depicts the difference in pipeline length (m) developed due to the difference in progress of Crew 1 and Crew 2. For illustration purposes Figure 16 was graphed from only one run. Comparing Figure 16 and Figure 3 from the Mokolo progress report, the same cyclic pattern is observed. However, the Safety Human Restriction M modelled into the as-is model restricts Crew 1 in Figure 16 at 500 m, while in Figure 3 some sort of larger restriction on the difference of pipe length between Crew 1 and Crew 2 was made. Similarities between the two graphs can be found when looking at their slopes. The slopes of both graphs are defined as the rate at which ΔD changes in time. The slope calculations are shown in Table 10. For the slope calculation of Figure 16 the incline marked in red was used. For the slope calculation of Figure 3 coordination's with roughly the same pipeline length was used.
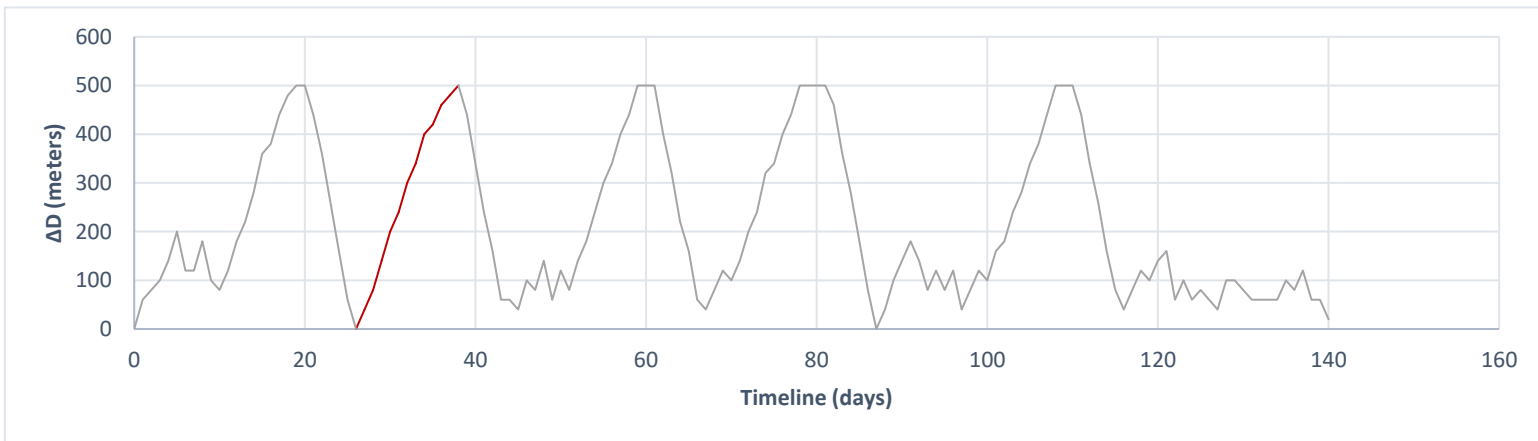
Figure 16: Difference in crew progress rate of the as-is model

Table 9: Crew progress difference comparison

	Real time output *(Figure 3)*	Simulation model *(Figure 16)*
Coordinates	(11;1289) to (13;1882)	(27;0) to (39;500)
Calculation	$Slope = \dfrac{\Delta D_{13} - \Delta D_{11}}{Week_{13} - Week_{11}}$ $Slope = \dfrac{1882 - 1289}{(13 \times 7) - (11 \times 7)}$ $Slope = 42.3571 \, \Delta D/Day$	$Slope = \dfrac{\Delta D_{39} - \Delta D_{27}}{Day_{39} - Day_{27}}$ $Slope = \dfrac{500 - 0}{39 - 27}$ $Slope = 41.6667 \, \Delta D/Day$

The values of the slopes are almost equal (0.0163% difference). If the simulation model did not adhere to the Safety Human Restriction, it could have peaked at the same ΔD seen in Figure 3 after the same weeks. Therefore, the model is specifically accurate or the purpose of the project.

3.3.2 Expert opinion

A session to present the findings of the simulation model was held with experts in this specific field. In this session the model was found significantly accurate for the purpose by expert opinion.

3.3.3 Sensitivity analysis

Sensitivity analysis serves as a way of validation the estimates. The as-is model was run 20 times every time, while changing the time deviation D and failure rates f_q estimates. Only the effect of increasing the parameters has been analysed, for it is assumed relatively the same effect would be seen when decreasing. The results are as follows.

Effect of increasing time deviation on model outputs

Table 10 contains the results of the output generated by increasing the time deviation by 100% and by 200%. The percentage change relative to the original seen in Table 10 proves to be significantly small. Therefore, the simulation model is insensitive to change in time deviation.

Table 10: Model output for increases in *D*-value

Output	Original	New Value	Percentage Change (%)	New Value	Percentage Change (%)
	D = 20%	D = 40%		D = 80%	
		(100% increase)		(200% increase)	
Total Duration (days/pipeline)	138	137	-0.72	138	0
Production rate (joints/day)	1.4412	1.4461	0.34	1.4358	-0.37
Total Cost (R/pipeline)	18021944.00	17995079	-0.15	18019364	-0.01
Crew 1 Utilization (%busy)	66.56	65.6	-1.44	65.63	-1.4
Crew 2 Utilization (%busy)	91.45	91.74	0.32	91	-0.49

Effect of increase in failure rates on model outputs

Table 11 contains the results of the output generated by increasing each failure rate value separately by 100% and by 200%. The percentage change to the original seen in Table 11 is significantly small for parameter f_{INSP2} and f_{INSP4}. However, parameters f_{INSP1} and f_{INSP3_1} is more sensitive.

Table 11: Model output for increases in f_q-value

Output	Original Value	New Value	Percentage Change (%)	New Value	Percentage Change (%)	New Value	Percentage Change (%)	New Value	Percentage Change (%)
		$f_{INSP1} = 20\%$		$f_{INSP2} = 20\%$		$f_{INSP3\_1} = 10\%$		$f_{INSP4} = 10\%$	
		(100% increase)							
Total Duration (days/pipeline)	138	145	5.07	137	-0.72	143	3.62	138	0
Production rate (joints/day)	1.4412	1.3667122	-5.17	1.4494	0.57	1.3917	-3.43	1.4399	-0.09
Total Cost (R/pipeline)	18021944.00	18352979	1.84	18065592	0.24	18214869	1.07	18037114	0.08
Crew 1 Utilization (%busy)	66.56	69.5	4.42	65.92	-0.96	63.89	-4.01	65.98	-0.87
Crew 2 Utilization (%busy)	91.45	86.4	-5.52	91.87	0.46	92.67	1.33	91.81	0.39
		$f_{INSP1} = 40\%$		$f_{INSP2} = 40\%$		$f_{INSP3\_1} = 20\%$		$f_{INSP4} = 20\%$	
		(200% increase)							
Total Duration (days/pipeline)	138	183	32.61	137	-0.72	156	13.04	143	3.62
Production rate (joints/day)	1.4412	1.0879	-24.51	1.4491	0.55	1.2769	-11.4	1.3876	-3.72
Total Cost (R/pipeline)	18021944.00	19955044	10.73	18230977	1.16	18720372	3.88	18242004	1.22
Crew 1 Utilization (%busy)	66.56	76.11	14.35	66.71	0.23	59.12	-11.18	64.04	-3.79
Crew 2 Utilization (%busy)	91.45	69.04	-24.51	91.12	-0.36	92.63	1.29	91.61	0.17

CHAPTER 4

4   RESULTS

This chapter consists of the analysis of the results of the as-is model, the results of the experimentation, as well as the implementation of the simulation model.

4.1   INTERPRETATION OF RESULTS

As seen in the model validation, the average production rate that the as-is model puts out is 1.4171 joints/day. The model also generated an average total pipeline cost of R18,235,354/4,000m and crew utilization listed in Table 12.

Table 12: Crew Utilization

|	Crew 1	Crew 2
Utilization (%)	62.99	91.39

To understand the values seen in Table 12, graphs were drawn from one simulation run. Figure 17 exhibits the daily production of Crew 1 and Figure 18 exhibits the production of the lining task executed by Crew 2. Figure 19 exhibits the daily exposed pipeline between the start of the joint being welded and the joint coated.
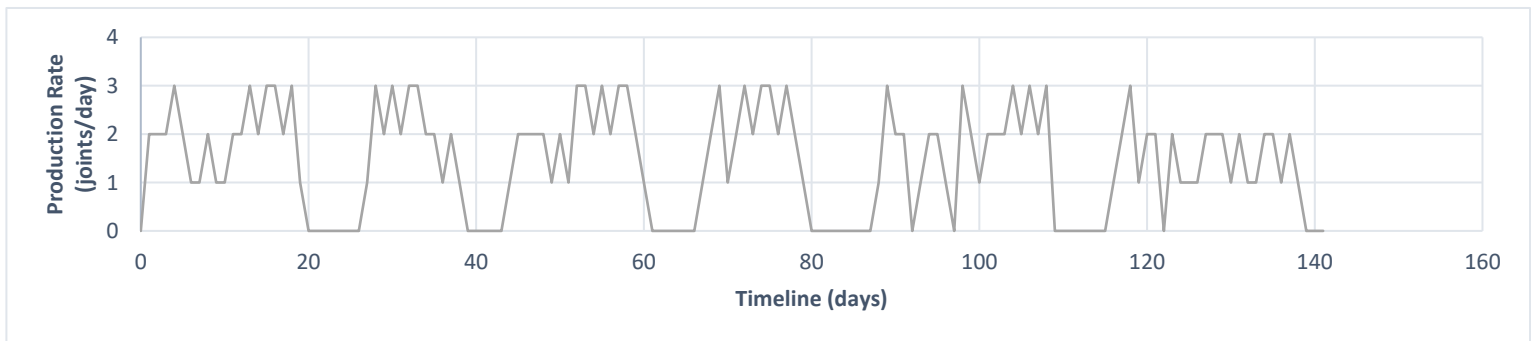
Figure 17: Daily production of Crew 1 of the as-is model
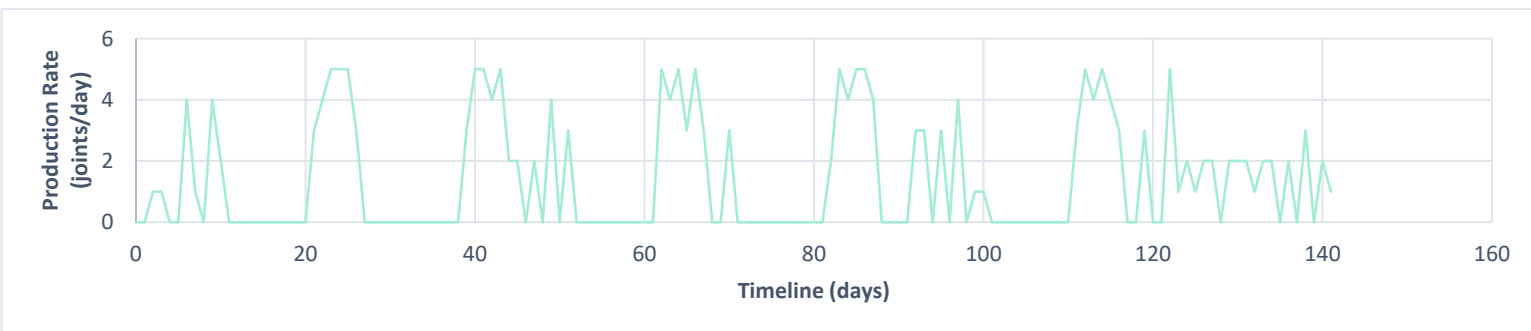
Figure 18: Daily lining production of Crew 2 of the as-is model
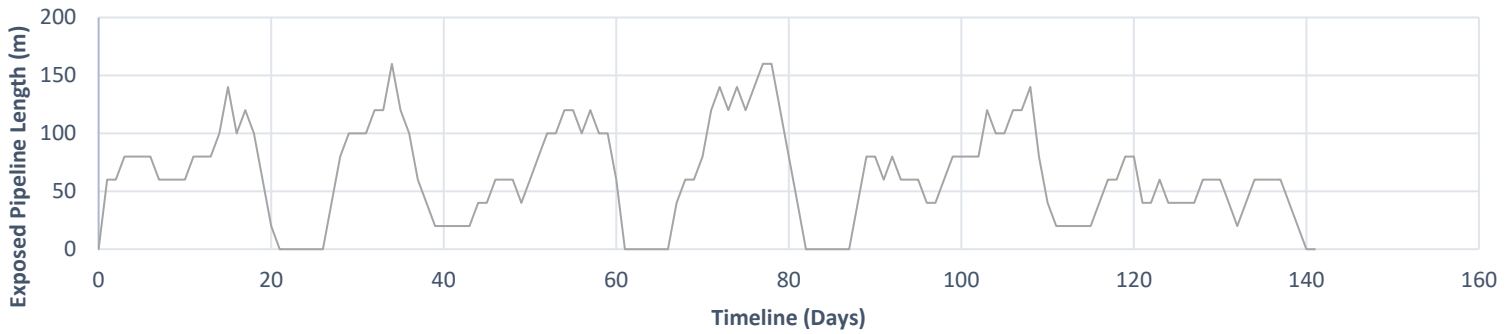
Figure 19: Exposed pipeline over time of the as-is model

The flat horizontal lines displayed at zero production rate in Figure 17 represents Crew 1 idling. This gives a cause for the 62.99% utilization of Crew 1 seen in Table 12. The correlation seen at the days in Figure 17 where Crew 1 idles and the spikes in Figure 18 is due to the Accessibility Control explained in the modelling logic section 3.2.2. As soon as Crew 2 has coated all available joints and moves on to complete the internal lining, Crew 1's progress is halted to make way for Crew 2 to access the inside of the pipeline.

In Figure 19 it is clear that the Management Exposure Restriction m of 300m is not reached, justifying that the Accessibility control, the Safety Human Restriction M and the Management Welding Restriction h are the only possible reasons causing Crew 1 to idle. Crew 2 has a 91.39 % utility. Crew 2 is responsible for the Lining and Coating tasks. The 8.61% idling is the start-up idling for the construction to get starting.

Aurecon strives for an optimal daily production rate of 3 Joints/day. Crew 1 sets the pace of its downstream construction processes. This means that, for the production rate to be optimal, the improvement opportunities should ensure that Crew 1 never idles. This means that the welding task (Crew 1) is the chosen bottleneck. A heuristic calculation follows to determine what the effect would be on the daily production rate if the idling waste could be eliminated from Crew 1.

If it is assumed that the percentage time spent on work is linearly related to daily production rate the extrapolation in Equation 7 can be made. 62% of Crew 1 capacity (x) produced the current daily production rate of 1.4171:

$$
\begin{aligned}
0.6299x &= 1.4171 \\
x &= 2.2497 \\
x &\approx 2.2 \text{ joints/day}
\end{aligned}
\tag{7}
$$

By eliminating Crew 1's idling the daily production rate can increase to 2.2 joints/day. This number would not reach the set target, but would represent a significant improvement from the as-is case. Improvement opportunities explored in the next section focusses on realising this 2.2 joints/day production rate and more.

4.2 EXPERIMENTATION

This section contains the results of the experimentation of the experimentation factors. The first sub-section explains the approach used to improve the production rate by eliminating the idling time of Crew 1. The second sub-section touches on improving the critical quality processes and the third discusses alternative scenarios.

4.2.1 Improving the production rate

To reduce the idling of Crew 1 the following approach was taken.

1. Decouple Crew 1 and Crew 2

Access holes are T-Shaped pipes added at intervals of A on the pipeline that gives Crew 2 access to the pipes without halting Crew 1's progress, and therefore decouples Crew 1 and Crew 2. A was modelled as 500m for one run. The distance of 500m between access holes converts to 8 access holes/4000m pipeline, and is the maximum distance allowed in order to adhere to the Safety Human Restriction M. This value was chosen to see whether there would be any effect on the output of the model.

This experiment resulted in production rate of 1.56 joints/day, which is a small increase. The Total cost reduced to R17,555,036. Figure 20 bellow exhibits the daily production of Crew 1. The flat horizontal lines at zero production rate seen in Figure 20 indicates that Crew 1 is still idling even though it has been decoupled from the activities of Crew 2.
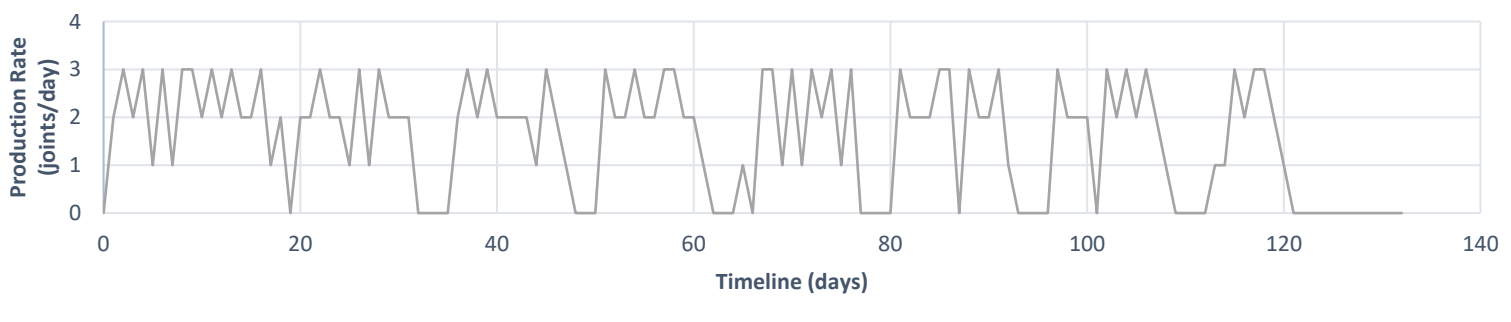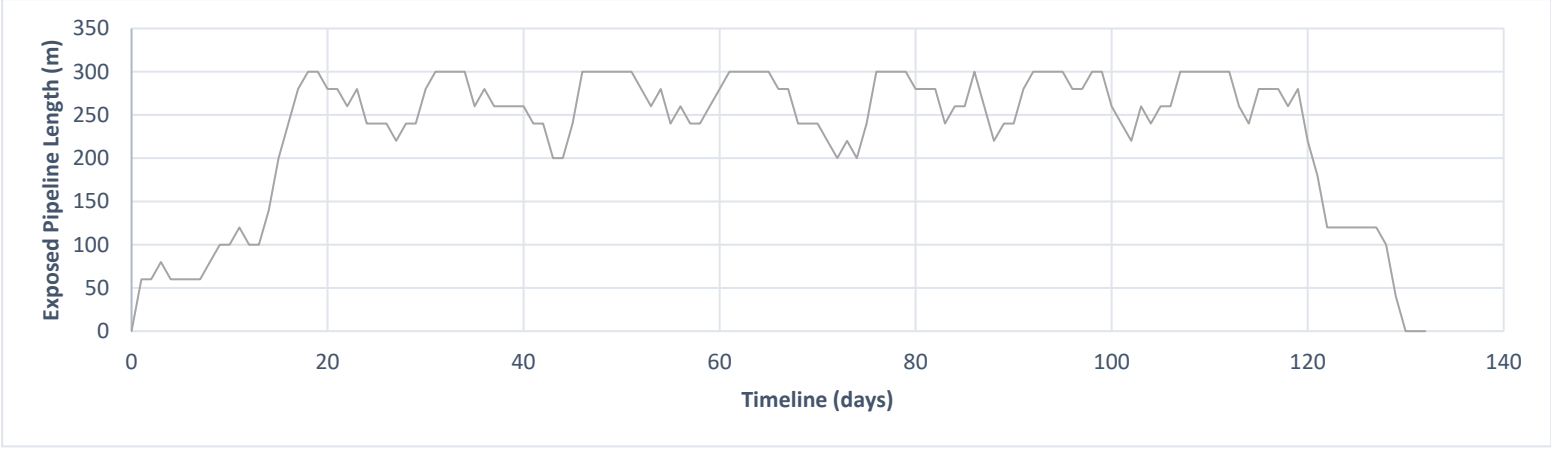

Figure 20: Daily production of Crew 1

The reason for the continued idling of Crew 1 is the Management Exposure Restriction m, as clearly indicated in Figure 21. The graph depicted in Figure 21 can be understood by comparing to Figure 23 and Figure 22. Figure 23 and Figure 22 exhibits the production by Crew 2, of the coating task and lining task, respectively. In Figure 23 the days when there are flat horizontal lines, correlate with the days where there are spikes in Figure 22, and vice-versa. This is because Crew 2 stops coating to line all available joints as soon as an access hole is appended to the pipeline. Crew 2's responsibilities are more time consuming than those of Crew 1, hence the constant long distances of exposed pipeline.
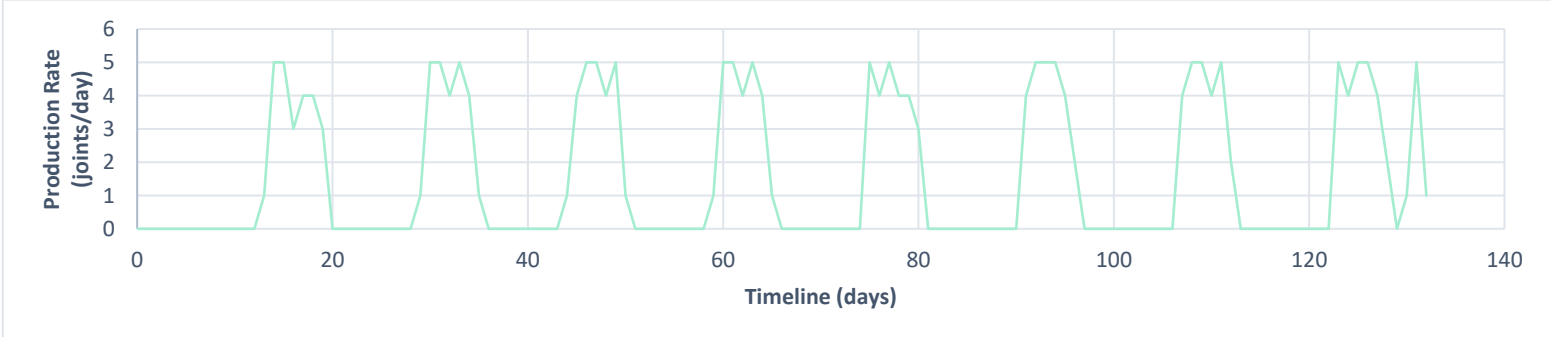
To improve the idling due to this constraint, Crew 2, being the bottleneck in this situation, needs to be more productive. To achieve this, a decoupling of the coating and lining tasks was modelled. This is explained in step 2.

Figure 21: Daily exposed pipeline over time

**Figure 23: Daily coating production of Crew 2**

Figure 22: Daily lining production of Crew 2

2. Decoupling coating and lining tasks

To decouple the lining and coating tasks, two Crew 2's were modelled so that the tasks could be executed simultaneously, as explained in the model logic. Again, one run was generated to visualise the effect of having two separate crews executing the coating a lining tasks, and having a *A* of 500m. The results generated a production of 2.16 joints/day and a total cost of R17,591,136. Figure 24 depicts the production of Crew 1 for this case. This result is close to the heuristic result discussed before.
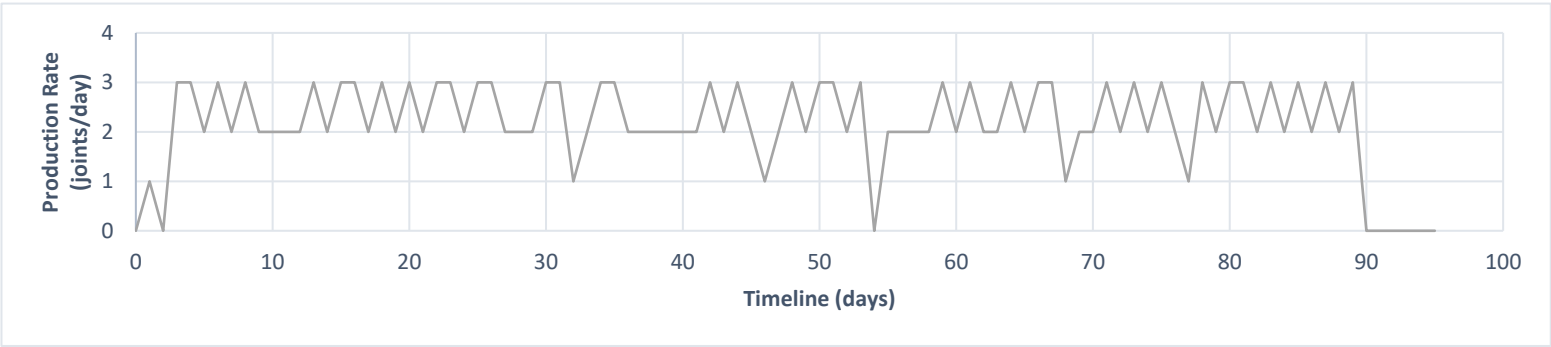
Figure 24: Daily production of Crew 1

From Figure 24, it is clear that Crew 1 now has almost no idling. The two downward spikes at day 2 and 54 are due to the Management Welding Restriction h. However, the idling of Crew 1 caused by h does not form part of this report's experimental factors. Figure 25 shows the daily coating production with no idling during the project, except at the start-up and end. This explains why the Management Exposure Restriction m of 300m is not reached in this scenario, as shown in Figure 26.
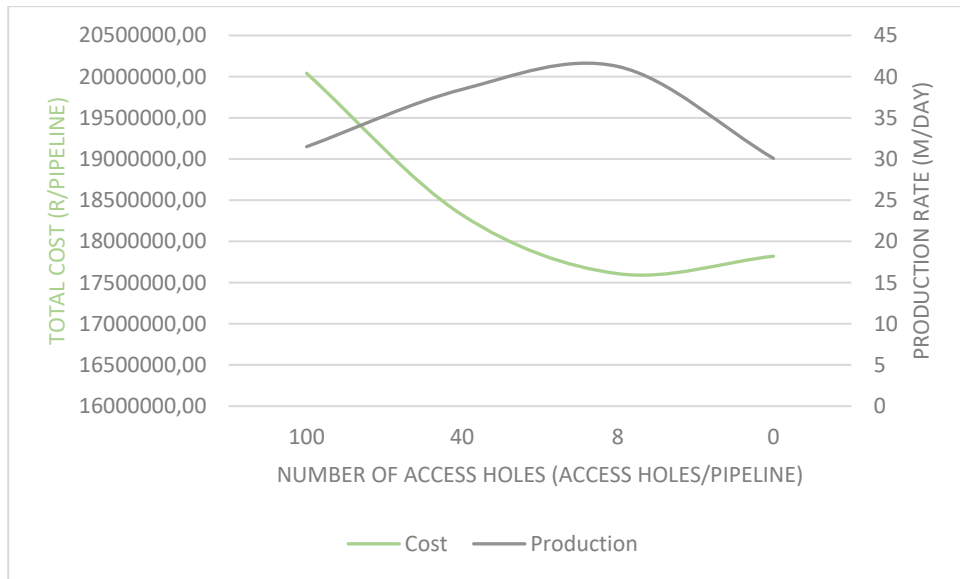

Figure 25: Daily coating production
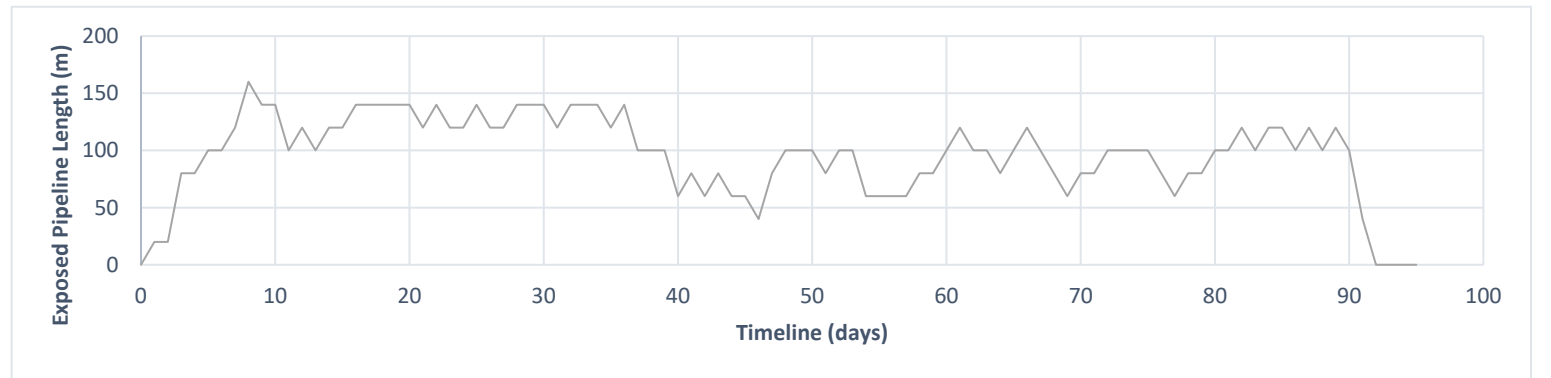
Figure 26: Daily exposed pipeline over time

3. Determining optimal distance between access holes

Experimentation was done on the distance between access holes following on the scenario above where coating and lining was decoupled. The result of 20 runs is exhibited in Figure 27.

Figure 27: Production rate and total cost for changing number of access holes

In Figure 27, the number of access holes equals 8 implies a distance between holes of 500m, corresponding to *A.* Fewer access holes would imply that the crews work slower. More access holes would improve the production time but would imply more welding of the additional joints and costs for the additional T-pieces. At 8 access holes, the total cost is the lowest and the production (m/day) is the highest. Therefore, access holes every 500m will be the optimal distance.

4. Summary

The approach followed by steps 1 to 3 can be summarised as an improvement opportunity to the as-is model. The results of changing the input *A* to 500m and decoupling the coating and lining tasks and running it 20 times, are depicted bellow. Figure 28 exhibits the distribution of the production rate. The total costs resulted in R 17,608,351. Table 13 shows the percentage change the improvement has on the on the daily production and total cost of the as-is model.
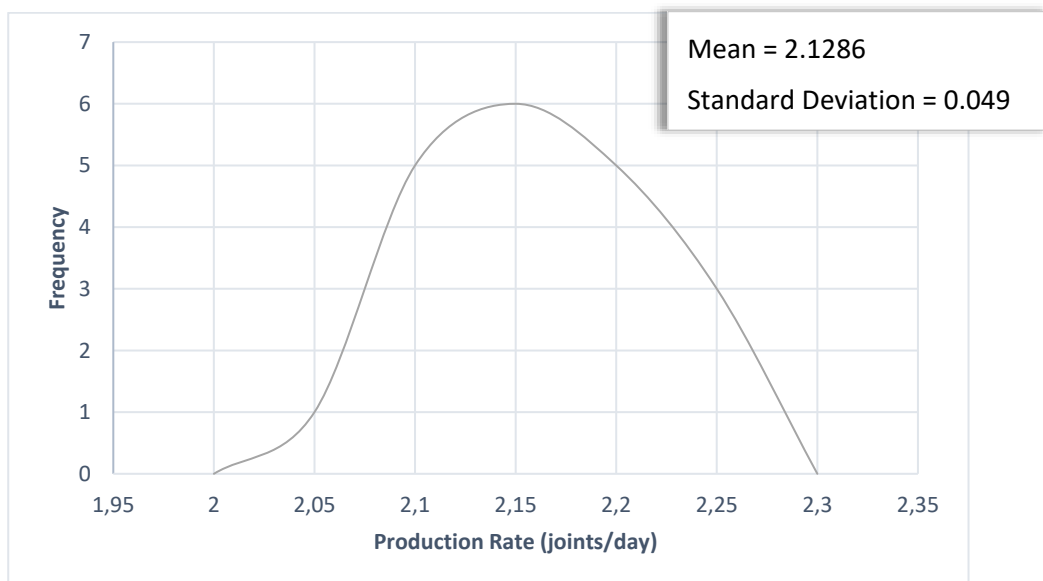
Figure 28: Daily production distribution of 20 runs

Table 13: Comparing improvement results

Output	Original	New Value	Percentage Change (%)
Production rate (joints/day)	1.4171	2.1286	50.21
Total cost (R/pipeline)	18235354	17608351	-3.44

4.2.2   Improving the quality

The sensitivity analysis performed to validate the data revealed two failure rates to which the model is sensitive. These failure rates are at Inspection 1 and 3_1 (INSP1 and INSP3_1 from Figure 9). The quality of the processes at these inspections can therefore be classified as critical. Focus can be given to these high-quality processes, by training the workers and implementing over-inspection on the grinding and coating processes, to decrease the failure rate and ultimately improve the quality.

4.2.3   Alternative solutions

There were two alternative solutions.

1.   Alternative coating type

The improved simulation model was run 20 times, with parameter k_t = Bituguard. The results were compared in Table 14. The percentage change is small and therefore possibly not worth pursuing. If it is considered worth-while, the coating specified in the contract would have to be changed.

Table 14: Model output of alternative coating type

Output	Epoxy	Bituguard	Percentage Change (%)
Production rate (joints/day)	2.1286	2.140787	0.57
Total cost (R/pipeline)	17608351	17594991	-0.08

2.   Alternative T-pipes

Consideration was given to alternative types of T-pipes, such as using normal length pipes with a hole to climb in. However, Aurecon bemoaned that the cutting holes on site damages the pipe and factories able to accommodate the longer T-sections are hard to find. It would however make a significant difference, since it would eliminate 8 joints per 4000m of pipeline.

4.3   IMPLEMENTATION

This section deals with practical implementation aspects of the simulation model as a management tool to Aurecon. Management has two responsibilities, namely planning and controlling. The simulation model assists the management in both these responsibilities.

4.3.1 Plan

The simulation model input parameters defined in Table 5 can be changed to accommodate different pipeline construction projects. The outputs can assist Aurecon in the planning phase of these projects to choose the optimal strategy for the specific scenario.

4.3.2 Control

The simulation model also aids as a tool to exercise control over a project. During the execution of a project the input parameters can be altered to specific incidents of the project and informed controlling decisions can be made. The simulation model also forms a framework for any other sequences and alterations desired by the users.

CHAPTER 5

5   <u>CONCLUSION AND FUTURE WORK</u>

The main objective of the project was to develop a simulation model to identify inefficient and constraining activities and find improvements opportunities for the construction process of large diameter pipelines. The following summarises the outcomes of the project:

- A discrete event simulation model was developed to incorporate all the relevant input data, experimental factors, as well as outputs.

- The model was successfully validated by performing sensitivity analyses on the estimated input variables, finding that the model outputs are generally robust.

- The model was used to simulate the as-is case and comparing the results to known results of a completed project. The model simulated a 1.4 joints/day, which compares well with the actual recorded 1.2 joints per day. The simulated cost of R18.2m for 4,000m could not be compared to actual.

- The simulation results were scrutinised to identify the constraints in the process. It was found that the idling time of the welding crew, caused by it waiting for the lining crew to access the pipe, represented the primary constraint.

- The model was then used to experiment to find improvement opportunities for this constraint. The introduction on access holes in the pipe, which decouples the two crews, was modelled. This resulted in a less than expected improvement, due to the welding crew still idling when reaching the Management Exposure Restriction m.

- To resolve this, the production of Crew 2 had to be improved by allowing for simultaneous execution of lining and coating (effectively adding another Crew 2), which then resulted in a balanced process where idling of Crew 1 (the chosen constraint), is minimised. The model simulated a production rate of 2.1 joints/day and a cost R17.6m (for 4,000m). The rate represents an improvement of 50% on the as-is case.

- An optimisation exercise was performed to determine the optimum spacing of the T-pieces and it was found that a spacing of 500m is optimal.

- Further improvement opportunities identified includes the improvement of grinding and coating quality, the use of T-pieces with full length pipes, as well as the use of alternative coating.

- It is also concluded that the model may be used as a management tool, which can aid Aurecon in the planning and control of future projects.

Future work could include gathering more accurate costs for the model, developing different sequencing for the process task and modelling multi-fronting. Multi-fronting means to function at more than one location of the pipeline simultaneously and sharing crews.

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Final Year Project Mentorship Form
2018

Introduction

An industry mentor is the key contact person within a company for a final year project student. The mentor should be the person that could provide the best guidance on the project to the student and is most likely to gain from the success of the project.

The project mentor has the following important responsibilities:
1. To select a suitable student/candidate to conduct the project.
2. To confirm his/her role as project mentor, duly authorised by the company by signing this **Project Mentor Form**. Multiple mentors can be appointed, but is not advised.
3. To ensure that the **Project Definition** adequately describes the project.
4. To review and approve the **Project Proposal**, ensuring that it clearly defines the problem to be investigated by the student and that the project aim, scope, deliverables and approach is acceptable.
5. To review and approve all subsequent project reports, particularly the **Final Project Report** at the end of the second semester, thereby ensuring that information is accurate and the solution addresses the problems and/or design requirements of the defined project.
6. Ensure that sensitive confidential information or intellectual property of the company is not disclosed in the document and/or that the necessary arrangements are made with the Department regarding the handling of the reports.

Project Mentor Details

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