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# Assessing the Transportation of Liquid Fuels in South Africa using Multi-Criteria Decision Analysis: A Conceptual Framework and Case Study

Thesis presented for the degree in: Masters in Engineering

In the Department of Civil Engineering

University of Cape Town

February 2016



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CLH MAR 003

Supervisor: A/Prof Marianne Vanderschuren

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## Abstract

With the recent unprecedented growth of many African economies, infrastructure investment has been flooding into the continent. Two key areas experiencing large growth in infrastructure development are the transport and energy sectors. This trend also continues to hold true in the South African development framework. The theme of this thesis encompasses both subjects of energy and transportation infrastructure which feature prominently in the countries development plans. When energy is discussed in South Africa, it is usually in the context of power generation and electricity distribution. This study focuses on another key component of the energy sector in the form of liquid fuel. Most of this energy is consumed for transportation purposes. The energy consumption of the transport sector in South Africa is large, totalling around 28% of Total Final Consumption (TFC) in the national energy balances. The bulk of this energy demand (97%) is in the form of liquid fuels, accounting for 84% of the national liquid fuel demand. This thesis focusses on the investigation of a Multi Criteria Decision Analysis (MCDA) model, which can be used to aid decision makers in the planning and assessment of liquid fuel transportation projects. A key feature of this thesis is the incorporation of a stochastic analysis in the MCDA model. There are two key motivations for assimilating a stochastic analysis in this investigation. The first one is the evaluation of incorporating such an analysis in an MCDA, as opposed to a more traditional sensitivity analysis. The second motivation is to assess the value of employing stochastic analysis as an input method for analysing a decision problem, where comprehensive field data can be substituted for a relevant range of simulated data. This thesis proposes a model which integrates the MCDA and stochastic analysis in the hope that it would provide a faster and more cost effective alternative for assessing certain liquid fuel transportation problems.



*Key words : Transport infrastructure ; Energy infrastructure ; Liquid Fuel ; Multi Criteria Decision Analysis ; Stochastic simulation ; Monte Carlo Simulation*

## **List of Acronyms and Abbreviations**

BPD – Barrels Per Day

CBA – Cost Benefit Analysis

EIA – Environmental Impact Assessment

GDP – Gross Domestic Product

IDZ – Industrial Development Zone

MCDA – Multiple Criteria Decision Analysis

MCS – Monte Carlo Simulation

O&M- Operational and Maintenance

REIPPP – Renewable Energy Independent Power Producer Programme

SAPIA – South African Petroleum Industry Association

TFC – Total Final Consumption

WSM – Weighted Sum Method



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# 1. Introduction

## 1.1 Background

Energy and transportation investment have fast become the most repeated buzz words when discussing infrastructure development in Africa. This is hardly surprising, considering the multitude of countries on the continent experiencing unprecedented economic growth in recent years. South Africa has not been immune to the use of these buzz words and despite not achieving similar high levels of growth, the nation is still one of the top ten investment destinations in Africa (KPMG Africa, 2014).

The theme of this thesis encompasses both subjects of energy and transportation infrastructure, **which feature prominently in South Africa's development plans. There are several major energy projects currently underway with many more in the pipeline.** When it comes to energy projects in South Africa, **one's first thought turns immediately to mega projects**, such as the much publicised construction of the Medupi coal fired power station, or the internationally acclaimed Renewable Energy Independent Power Producer Programme (REIPPP). While these are electrical generation projects, another large contributor to the South African energy economy comes in the form of liquid fuels. The energy consumption of the transport sector in South Africa is large, totalling around 28% of Total Final Consumption (TFC) in the national energy balances. The bulk of this energy demand (97%) is in the form of liquid fuels, accounting for 84% of the national liquid fuel demand (DoE, 2009; IEA, 2011). The infrastructure required to distribute these fuels throughout the nation is immense. Large ports, refineries and depots are strategically placed for distribution, while the four major modes utilised for transporting liquid fuels are road freight, rail freight, maritime shipping and pipelines.



A study published by Transnet pipelines (2014:2), projects that fuel demand in South Africa will increase by more than 250% in the next 30 years (Figure 1). It is evident that with this demand, comprehensive distribution networks will be required from refineries and import harbours, to major cities and inland markets.

Liquid fuel products	2014	2015	2016	2017	2018	2019	2020	2023	2033	2043
Jet	2,6	2,6	2,7	2,8	2,6	2,8	2,9	3,1	3,9	4,9
Diesel	13,6	14,2	14,8	15,5	16,2	16,9	17,7	20,2	31,9	52,5
Petrol	13,5	13,6	13,7	13,8	14,0	14,1	14,2	14,6	16,0	17,6
Other	4,5	4,5	4,5	4,5	4,7	4,6	4,5	4,6	4,8	5,1
<b>Total</b>	<b>34,1</b>	<b>34,9</b>	<b>35,7</b>	<b>36,6</b>	<b>37,5</b>	<b>38,4</b>	<b>39,4</b>	<b>42,5</b>	<b>56,6</b>	<b>80,1</b>
Annual growth	2,8%	2,3%	2,3%	2,4%	2,4%	2,5%	2,5%	2,6%	3,1%	3,7%

The graph on the right below shows the liquid fuel demand (including other products) for South Africa and non-South African supplied from or via South Africa for the period 2014 to 2043.

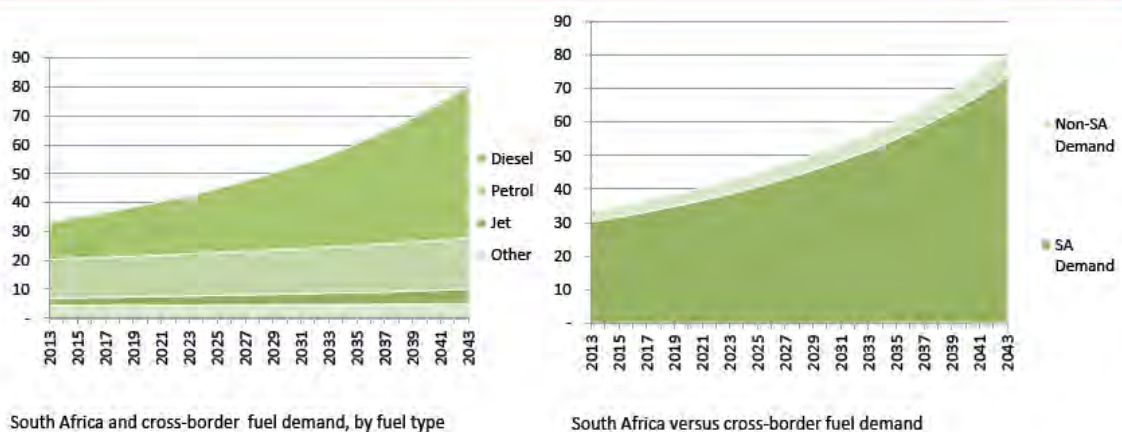


Figure 1 : South Africa refined fuel demand, by fuel type (billion litres per annum), (Transnet, 2014)

This thesis focusses on the investigation of a Multi Criteria Decision Analysis (MCDA) model, which can be used to aid decision makers in the planning and assessment of liquid fuel transportation projects. A key feature of this thesis is the incorporation of a stochastic analysis in the MCDA model. There are two key motivations for assimilating a stochastic analysis in this investigation. The first one is the evaluation of incorporating such an analysis in an MCDA, as opposed to a more traditional sensitivity analysis. The second motivation is to assess the value of employing stochastic analysis as an input method for analysing a decision problem, where



comprehensive field data can be substituted for a relevant range of simulated data. The hypothesis for initiating such a substitution is that simulating data could significantly reduce the time taken for decision analysis research, as well as, prove to be far more cost effective. In order to test this method, a developed model, incorporating a MCDA with a stochastic analysis, was applied to a relevant liquid fuel transportation case study in South Africa.

The developed model has been applied to a relevant case study in the form of the Project Mthombo crude oil refinery, which is being studied for development at the Coega Industrial Development Zone (IDZ) in the Eastern Cape. Although the case study is specific to this location, the MCDA analysis will focus on a portion of the distribution network which is generic to most fuel distribution networks in the country. Liquid fuel can be sourced from various locations and supplied to many consumer and retail nodes (Dodds & McDowall, 2012). The generic distribution path of interest for this study covers the link between the storage node of the supplier, to the terminal storage node for retail distribution. This is further illustrated in Figure 2.

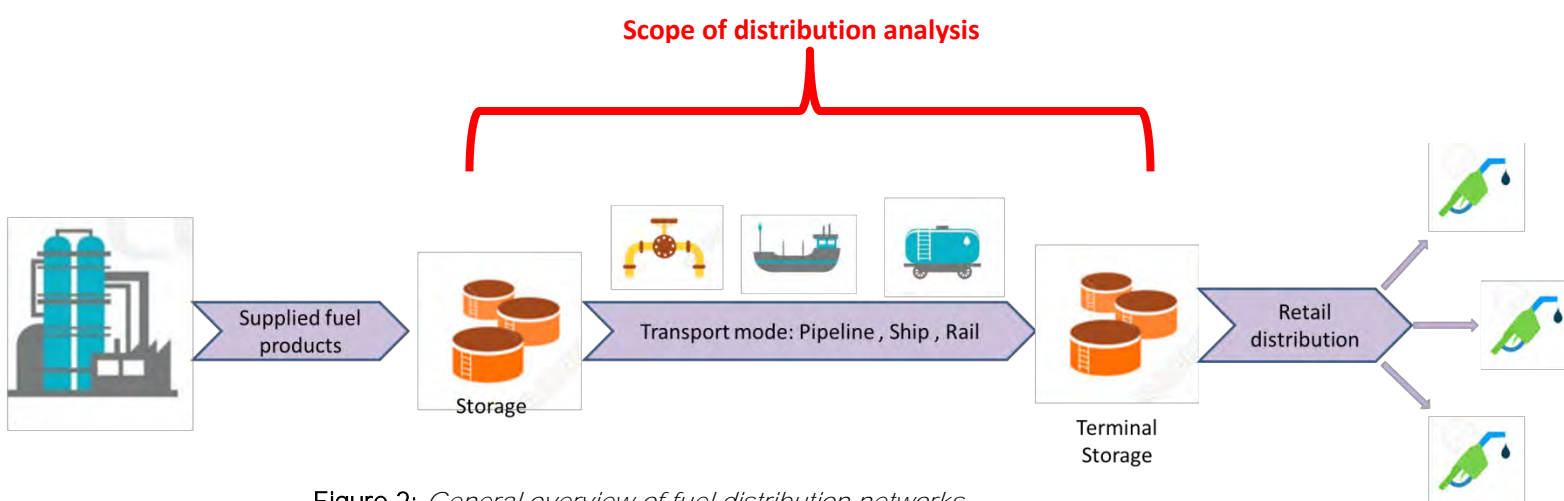


Figure 2: General overview of fuel distribution networks



## 1.2 Research Methodology

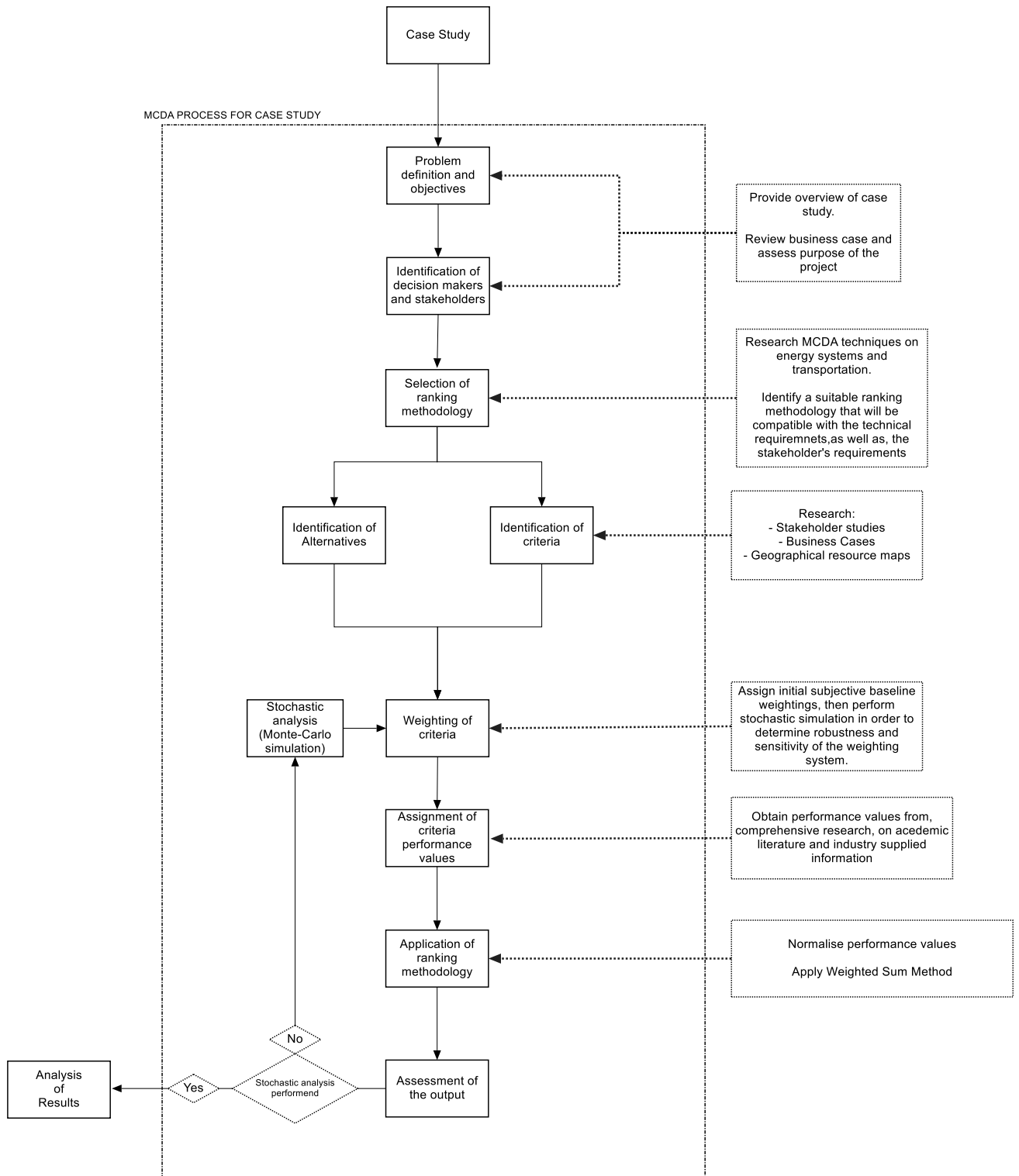
The desired outcome of this thesis is to assess a high level generic model which will allow any user to apply specific data to a relevant case study of this nature. Where standard MCDA studies usually require a significant combination of qualitative and quantitative data, the scope of this thesis, is to provide a function for inputting relevant data in the developed model without actual first hand data collection. The model will be assessed by applying it to the Project Mthombo case study, which has been elaborated upon further on in this thesis. The data utilised in the case study analysis has been thoroughly researched and obtained from a wide variety of academic and commercial resources. This research was conducted in order to accumulate accurate data which could be inputted into the MCDA for the case study. The results generated from this data, would provide a reliable datum on which to compare various stochastic simulations.

A crucial component of most MCDA assessments is the weighting of criteria. In order to obtain relevant and accurate weightings, standard practice requires a wide variety of consultation with stakeholders, professionals and academics. As the scope for this thesis does not allow for such a wide consultation, a stochastic simulation has been adopted in order to establish the variance of probable outcomes. This is done by employing Monte Carlo Simulation (MCS) on the initial normalised performance rankings and weightings in the MCDA. By utilising the stochastic simulation, more information can be obtained on the robustness of the initial weighting and performance values. This, ultimately, provides a form of sensitivity analysis, which will indicate the likelihood of a different outcome in the analysis, due to the variability of the performance values and weightings. Once the developed MCDA process for the case study has been completed, a comprehensive analysis of the results and conclusions has been provided.



### 1.3 Overview of the Process

The flow diagram below describes the step by step process that this thesis follows. The blocks with the dotted lines on the right give a brief indication of the action required in each step.





## 1.4 Overview of MCDA

Many decisions, regarding large transportation and infrastructure projects, involve several discrete alternatives and criteria. The results of these decisions are usually characterised by complex repercussions, conflicting stakeholder interests and general uncertainty. Multi Criteria Decision Analysis (MCDA) is a tool that can be used to aid decision makers on these complex projects, which assesses the many related discrete alternatives, while encompassing all relevant stakeholders and criteria. A key characteristic of Multi Criteria Decision Analysis, as opposed to more conventional methods of assessing large projects, such as Cost-Benefit Analysis (CBA), is that the powerful analytical characteristics of the tool are further enhanced by an inclusive criteria system which does not have to be monetised in order to be equated.

The benefits of MCDA relate largely to the process. MCDA, typically, involves several key stages, which are collectively referred to as the MCDA process. Numerous authors in literature have identified stages of the MCDA process and only minor differences exist, such as the order in which the stages are undertaken. The stages selected for this particular study include:

**Stage 1** – Defining the Decision Problem and Objectives

**Stage 2** – Identification of Decision Makers and Stakeholders

**Stage 3** – Selection of the Ranking Methodology (or Aggregation Technique)

**Stage 4** – Identification of Alternatives

**Stage 5** – Identification of Criteria

**Stage 6** – Weighting the Criteria



**Stage 7 – Assignment of Criteria Performance Values**

**Stage 8 – Application of the Ranking Methodology (or Aggregation Technique)**

**Stage 9 – Assessment of the Output**

(Hyde *et al.* 2011)

Multi criteria methods differ in the way the idea of multiple criteria is operationalised. In particular, each method shows its own properties with respect to the way of assessing criteria, the application and computation of weights, the mathematical algorithm utilised, the model to describe the system of preferences of the agent facing decision-making, the level of uncertainty embedded in the data set and the ability for stakeholders to participate in the process (De Montis *et al.* 2000). Thus, it is crucial to ensure that the multi criteria method, selected for a particular decision problem, provides a suitable and appropriate model for that problem, so as to ensure an accurate and relevant outcome.

### **1.5 Content of the Report**

Chapter 2 of this report establishes the case study which has been applied for the MCDA process. An initial brief of the case study is first presented followed by a summary of points which indicate the relevancy of the case study for this report. The second section of Chapter 2 is the detailed breakdown for each of the nine steps in the adopted MCDA process. This information presented in the 9 step process is compiled from extensive research. This is 9 step process is where the main MCDA is performed in this report. The chapter ends with the final stage of the process which presents the ranking order outcome of the MCDA.



Chapter 3 deals with the stochastic simulation of the MCDA results. An overview of stochastic simulation methods is presented with a focus on Monte Carlo Simulation. A detailed description of MCS is specified, as well as, the specific developed equation which has been utilised for the simulation in this report. This is followed by a detailed presentation of the results of the MCS. The chapter ends with, the final comparison of the ranking order outcome for the stochastic simulation, versus, the ranking order outcome of the initial MCDA results in chapter 2.

Chapter 4 provides an investigation of the results. The first portion of this chapter deals with the analysis of the case study results. An exploration of the final outcome of the initial MCDA outcome and the MCS outcome is scrutinised individually, followed by a comparative analysis of the two results. The second part of the chapter offers insight into the general applications and limitations that the MCS can provide for decision problems, such as, the one in this case study. The chapter ends with a final particular conclusion of the case study results.

Chapter 5 provides the final conclusions for this report. The conclusion focuses on the analysis methods and tools adopted for this study. A deduction is made on the suitability of MCDA in liquid fuel transportation projects. Further conclusions are made on the usefulness of employing MCS in an MCDA analysis and more specifically, the effectiveness of MCS in improving efficiencies and costs in decision making problems of this nature.



## 2. Case Study – Transporting Liquid Fuel Product from Project Mthombo Refinery to Gauteng

### 2.1 Background

Project Mthombo is a crude oil refinery project that is proposed to be built at the Coega Industrial Development Zone (IDZ) in the Eastern Cape, South Africa. A key factor in determining the **feasibility of this mega project is the viability of transporting the refineries' liquid fuel products from Coega, to the country's largest fuel market in Gauteng.**

The much publicised refinery is being led by the South African national oil company PetroSA. Recent developments have resulted in PetroSA partnering with the Chinese state oil company Sinopec as the anchor partner and the South African Industrial Development Corporation (IDC) as the national funding partner (PetroSA ,2012) .The refinery is planned to produce 300 000 barrels per day, which is currently more that the total demand of Gauteng. It will not be economically viable to export the refined crude to overseas customers, as there is already an abundance of refined products in the international market that can be produced at a lower cost. Thus, it is essential for the domestic fuel market to make up most of the demand from Mthombo, for the refinery to be feasible.

The majority of fuel demand in South Africa originates from the industrial and commercial power house of Gauteng. This province takes up 1.4% of total land mass in the country but produces 33.7% of national GDP and contains around 23% of the total population of South Africa ( Mervan et al). Fuel demand in Gauteng far outstrips all other provinces in the country with around 39% of total national consumption (Figure 8, Appendix A).



The Primary focus of this case study will be to use the proposed MCDA model in order to determine the optimum method of transporting liquid fuels from Project Mthombo to Gauteng.

## 2.2 Relevance of the case study

Since the entry of Sinopec into the deal in late 2012, a detailed feasibility study regarding the economic viability of Project Mthombo has been underway. According to PetroSA, a further study has been commissioned in order to establish the method of transporting the refinery's products from Coega to Gauteng. This aspect of the project will be the main focus of this case analysis.

### *Analysing new route options*

Of all the possible scenarios and routes available, PetroSA has already decided on two final alternatives to be analysed. Namely, building a new pipeline from Coega to Johannesburg via Bloemfontein, or establishing a shipping route from Coega to Durban and piping the liquid products **through Transnet's Multi-Product Pipeline**. This study will assess several scenarios, including options such as road freight, rail freight and different pipeline routes. This will help in determining whether initial intuition on disregarding these routes is warranted or not.

### *Comparing final Decisions from each study*

It is not known what tools PetroSA and Sinopec are utilising in the assessment of the feasibility study but it is hoped that once the MCDA of this case study is completed, the results will be able to be compared to the final feasibility study issued by Sinopec. This will be able to provide useful academic information and possibly shed light on how project decision outcomes differ with different decision tools.



### *Establishing a planning frame work for liquid fuel transportation in South Africa*

The potential for future development of liquid fuel infrastructure in Southern Africa is significantly large. Some of the largest natural gas finds, for many years, have been discovered off the east coast of Tanzania and Mozambique. There are already calls for pipelines to be built from these **fields to South Africa for monetisation. Within South Africa's** borders, there have been significant gas finds off the North West coast (Sunbird, 2014) and the hotly contested shale gas in the Karoo region. Furthermore, South Africa is a net importer of liquid fuel with the inland region of Gauteng continuously growing in its appetite for energy. The National Development Plan (NDP) recognises this growing need for liquid energy projects and has outlined key strategic objectives for the sector. The rather ambitious goal of this paper is to establish relevant tools and criteria which could contribute to an effective framework for the development of liquid fuel transportation and supply networks in South Africa.

### 2.3 The MCDA Process

#### Stage 1 – Defining the Decision Problem and Objectives

A clear objective for the use of Multi Criteria Decision Analysis is to develop a framework that provides a broad based and structured approach to decision making in liquid fuel transportation projects.

The specific objective of this case study can be summarised as determining the most feasible method for transporting liquid fuel from Coega to Gauteng in an inclusive and efficient way.



The main decision problems have been defined as follows:

- Create a stable and viable customer base for the Project Mthombo refinery.
- Focus on broad, all-encompassing options which align to relevant development plans
- Ensure the long term supply of liquid fuel for Gauteng and surrounding regions.
- Ensure that the project contributes to the broad based socio-economic development of South Africa
- Ensure compliance to all environmental and legal legislation

## Stage 2 – Identification of Decision Makers and Stakeholders

The following list of entities was identified as the main decision makers and stakeholders:

Main decision makers:

- Petro SA & Transnet

Main Stakeholders:

- Local and Provincial Government Departments
- Local Community Stakeholders
- Sanral
- Road Freight Association
- Petroleum Agency South Africa
- National Treasury
- Department of Transport
- Department of Energy
- Department of Public Work



### Stage 3 – Selection of the Ranking Methodology (or Aggregation Technique)

The Weighted Sum Method (WSM) was selected as the aggregation technique for this analysis.

This is due to the simplicity and wide application that this method presents for an analysis of this nature. It is also important to note that, although WSM is a simple aggregation technique, it is by no means less adequate than other techniques for a study like this. WSM involves calculating the sum of the product of each criteria performance value, by the corresponding weighting allocated to that particular criterion. This can be described mathematically as follows:

$$(S_i) = \sum_{j=1}^n x_{ij}w_j \quad i = 1, 2, \dots, m$$

Where:  $x$  = performance value

$w$  = weighting

$i$  = column for each option

$j$  = row for each criteria

The resulting total weighted sum scores can then be compared directly against one another. A negative value is given to criteria where, the higher the value, the less desirable it is, such as costs and environmental impact. For all desirable criteria, the weighting is denoted as positive. The alternative, with the highest total weighted sum, is considered the best option.



#### Stage 4 – Identification of Alternatives Options

The first thing to review when deciding possible route options for this case is to establish what are the most feasible ways of transporting bulk liquid fuel. It is clear, from literature and many examples in real operations around the world, that there are four main modes of transporting liquid fuel, namely:

- Rail Freight
- Road Freight
- Pipeline
- Coastal Shipping

These four modes already account for 98% of all fuel transported in South Africa (Transnet, 2014).

An overview of each modes role in the transportation of liquid fuel has been provided in the relevant MCDA process later on in this paper.

The four scenarios to be compared:

**Option 1** – Transporting the fuel by existing Rail from Coega to Gauteng

**Option 2** – Transporting the fuel by a new pipeline from Coega to Gauteng

**Option 3** – Transporting the fuel by developing a new pipeline from Coega to Durban that connects to the existing Transnet operated Multi-Product Pipeline (MPP)

**Option 4** – Transporting the fuel by ship from Coega to Durban then connecting to Gauteng via the MPP



Note: Although road tanker transportation is a major and well established mode for transporting liquid fuel, there has been a directed policy shift away from road freight in South Africa. This has been implemented by national government policy, as well as major freight operators, such as Transnet who want to get freight off the roads. Road freight has continued to grow, over the years, which has resulted in highly congested national roads. This is not only inefficient, but has shown to pose some serious safety risks over the years (Transnet, 2014). As a result of this policy direction, it was decided to not consider road tankers as a viable mode of transportation in this study.

Figure 3, on the next page, provides a basic route indication of the scenarios to be assessed. The map utilised, is compiled by the Petroleum Agency of South Africa. The Petroleum Agency is mandated to advance and manage the exploration and exploitation of natural petroleum resources in the country. Map 01 is published by the agency and provides a detailed assessment and geographical outlay of energy resources in South Africa. The information illustrated on this map is highly relevant to this study and will provide insight on some influencing criteria for the different scenario options.



- + + + + Option 1 – Transporting the fuel by existing rail
- Option 2 – New pipeline from Coega to Gauteng
- Option 3 – New pipeline to Durban connecting to MPP
- Option 4 – Shipping route to Durban connecting to MPP

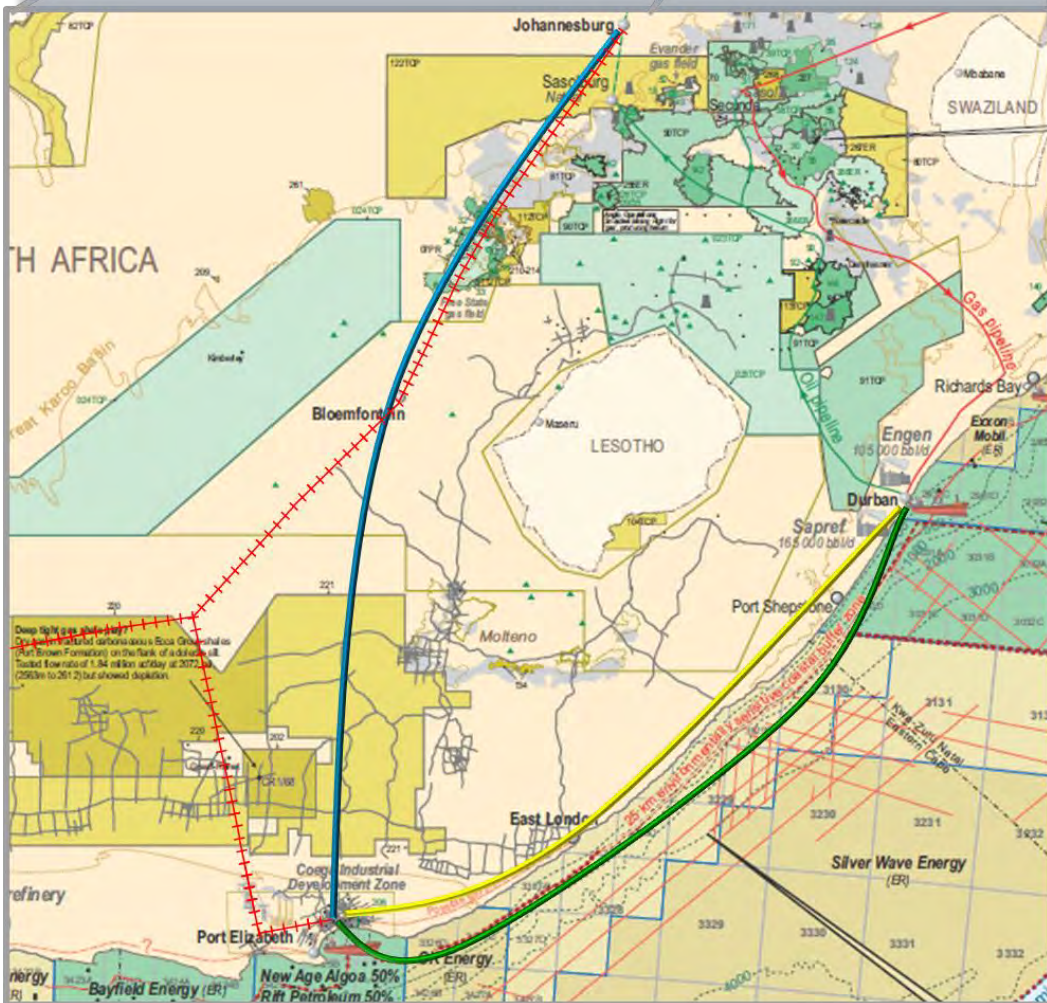
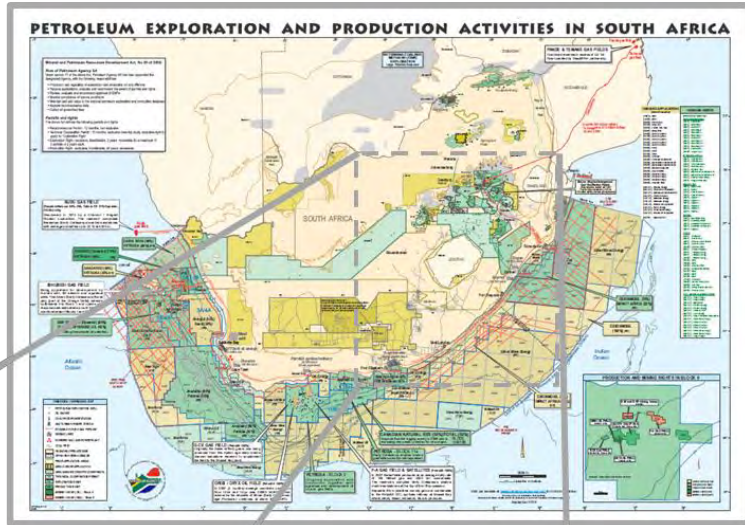


Figure 3: Illustration of Possible Scenario Options under Investigation (Adapted from Petroleum Agency SA)



## Stage 5 – Identification of Criteria

Assessment criteria for energy transportation systems can be sorted into four broad groups; technical criteria, economic criteria, environmental criteria and social criteria. A comprehensive summary of the criteria that fall under these groups was obtained from literature (Wang et al., 2009). The following criteria deemed relevant for assessment were selected as follows:

### Technical:

- Energy Efficiency
- Flexibility

### Economic:

- Investment cost
- Operation and maintenance costs

### Environmental:

- CO<sub>2</sub> emissions
- Land use

### Social:

- Safety
- Social acceptability
- job creation



- Social Benefits
- Alignment to strategic plans

## Stage 6 – Weighting the Criteria

Criteria weightings are used to denote the relative impact and importance of each criterion in the decision problem. This is usually done by assigning the weighting on a common scale. For this study, the weighting was assigned on a scale between 0 and 1. Weightings tend to have a highly influential role in affecting the results of a decision analysis. Consequently, it is imperative to obtain rational and reliable criteria weights. Generally, criteria weightings are either obtained by a mathematically objective method or in a subjective manner based on the preferences of the decision makers (Wang et al., 2009). Subjective weighting on any single criterion can vary wildly depending on the decision maker. Clearly, the weighting for an environmental criterion would be more important to a stakeholder such as an environmental NGO, as opposed to a freight logistics company.

In many cases, certain criteria weightings may depend on intimate knowledge held by a decision maker, regardless of the weighting method employed. Thus, in many cases, there may always be a certain degree of discrepancy and uncertainty with the values obtained for weighting. A main point of interest of this study is to utilise stochastic analysis in order to determine the influence that subjective criteria weightings can have on the variance of a decision analysis outcomes. Thus, a subjective rank order weighting method was utilised for this case study.

The rank order weighting method recognises the relative importance of some criteria over others (Wang et al., 2009). Essentially the weighting method distributes the criteria weights ( $w$ ) as follows:



$$w_1 \geq w_2 \geq \dots \geq w_n \geq 0$$

$$\text{Where : } \sum_{i=1}^n w_i = 1$$

Therefore, for this case study, the relative criteria weightings were established as follows:

**Investment cost (W = 0.175) ≥ Operation and maintenance costs (W = 0.175) ≥ Energy Efficiency (W = 0.125) ≥ Flexibility (W= 0.125) ≥ CO<sub>2</sub> emissions (W = 0.0075) ≥ Land use (W = 0.0075) ≥ Safety ≥ Social acceptability (W= 0.003) ≥ job creation (W= 0.003) ≥ Social Benefits (W= 0.003) ≥ Alignment to strategic plans (W= 0.003)**

## Stage 7 – Assignment of Criteria Performance Values

### Technical:

- Efficiency – capacity calculation

Efficiency describes how much useful energy we can get from an energy source. Efficiency is used to evaluate the performance of an energy system in the form of the Energy Coefficient. The Energy Coefficient is defined as the ratio of the output energy to the input energy. For any energy system, it is desirable to have efficiency as high as possible. Efficiency is an important criterion and is used to evaluate many energy systems around the world.



For this case study, the efficiency of each transportation system was calculated by the net energy required to transport a constant volume of liquid fuel. A volume of liquid fuel can be measured in terms of energy.

Where there was not enough information found in literature for direct calculation of efficiencies, reliable figures on the efficiencies of each mode was extracted from comprehensive studies and energy models such as the UK MARKEL (Krewitt & Schmid, 2004)..

#### Option 1

The efficiency of transporting liquid fuel by rail is described by the TECHPOL data base as an average of **89%** for all trains (Krewitt & Schmid, 2004).

#### Option 2 & 3

The efficiency for transporting liquid fuel by pipeline varies drastically, depending on the diameter of the pipeline, the formation of pumps and compressors, internal wall friction coefficients and certain other factors. Thus, modelling investment costs, efficiencies, utilisation factors and other performance indicators for pipelines is rather complicated. An example of this complexity is the fact that throughput of fuel is not directly proportional to the diameter of the pipeline. Throughput can also be increased by increasing pressure and, subsequently, flow rate through a pipe, albeit at a higher energy cost affecting efficiency.

Traditional engineering design of pipeline economics includes plotting throughput vs efficiency vs cost and finding an intersecting optimum. This level of analysis is beyond the scope of this paper. Values for pipeline performance factors were, thus, obtained from the



international TECHPOL data base compiled by Krewitt and Schmid (2004) and can be found on Table 8, Appendix A. The pipe size used for option 3 and 4 will be a 24" or 600mm diameter pipe which is the same as that of the Transnet MPP. The Transnet MPP has been designed for future demand growth for the next 20 years and is a sufficient size for this study. From Table 8 it can be seen that the efficiency of a 600mm pipe is given as **95%**.

#### Option 4

The efficiency of transporting liquid fuel by ship is described by the TECHPOL data base as an average of **95%** for all ships. (Krewitt and Schmid, 2004).

#### Flexibility

Flexibility is a performance parameter which indicates each transportation systems' ability to adapt to change. More specifically, for this study, is assessing how quickly the selected system can be adapted, in order to meet its design goals in a changing environment. A score card, developed from a conceptual framework found in literature, was used as an assessment tool in order to obtain a subjective performance score for each route option (Pujawan, 2004). The scores were based on a scale from 0 – 100 in order to simplify the normalisation of the performance values during analysis.



Option 1 – Transporting the Fuel by Existing Rail

<b>Description</b>	<b>Score</b>
It is both technically easy and economical, to mix different products into a delivery load	90
In case of emergency needs, speeding up the delivery of products is possible either by choosing a faster mode of transportation or by other means	60
It is possible to satisfy the delivery order of a customer from more than one source	75
The system can change the quantity and type of product in a short space of time	80
The costs implication of changing the quantity, types and/or the due date of delivery is low	50
<b>Average</b>	<b>72</b>

Option 2 – New Pipeline from Coega to Gauteng

<b>Description</b>	<b>Score</b>
It is both technically easy and economical, to mix different products into a delivery load	62
In case of emergency needs, speeding up the delivery of products is possible either by choosing a faster mode of transportation or by other means	40
It is possible to satisfy the delivery order of a customer from more than one source	35
The system can change the quantity and type of product in a short space of time	50
The costs implication of changing the quantity, types and/or the due date of delivery is low	70
<b>Average</b>	<b>52</b>



Option 3 – New Pipeline to Durban Connecting to the MPP

<b>Description</b>	<b>Score</b>
It is both technically easy and economical, to mix different products into a delivery load	62
In case of emergency needs, speeding up the delivery of products is possible either by choosing a faster mode of transportation or by other means	40
It is possible to satisfy the delivery order of a customer from more than one source	35
The system can change the quantity and type of product in a short space of time	50
The costs implication of changing the quantity, types and/or the due date of delivery is low	70
<b>Average</b>	<b>52</b>

Option 4 – Shipping Route to Durban Connecting to the MPP

<b>Description</b>	<b>Score</b>
It is both technically easy and economical, to mix different products into a delivery load	30
In case of emergency needs, speeding up the delivery of products is possible either by choosing a faster mode of transportation or by other means	55
It is possible to satisfy the delivery order of a customer from more than one source	95
The system can change the quantity and type of product in a short space of time	70
The costs implication of changing the quantity, types and/or the due date of delivery is low	55
<b>Average</b>	<b>61</b>



## Economic:

### Investment cost

Investment costs incorporate the total capital outlay required to produce the required project. This includes all construction costs, as well as costs relating to studies, land acquisition and all necessary procurement items. The investment costs were based on the required system required to meet a fuel demand of 24 000 m<sup>3</sup>/ day. This is currently the planned capacity of the MPP and was used as a baseline. For this reason, capacity was not assessed as an actual performance criterion, as many other criteria performance values were based on this minimum required fuel demand.

### Option 1

Transporting the required amount of liquid bulk by rail would require a new fleet of rolling stock. This scenario assumes that there will be enough capacity on existing railway lines in order for the required rolling stock to operate. The average cost of a new locomotive is found to be \$4 000 000 per unit: (T&L insights, 2014). The average cost of a new tank car is between \$120 000 and \$175 000 (Zarkh & Zhang, 2015). A standard fuel car has a storage capacity 87 000 litres. This equates to 87m<sup>3</sup> per car. Thus, the total amount of fuel cars required to meet the demand capacity would be 286 cars per day. Based on an 11 day turnaround with 6 train sets of 2 locomotives each per day, the number of fuel cars required would be estimated at 3146 cars and 132 locomotives. The capital expenditure can then be calculated as follows:

$$\text{locomotives} [132 \times \$4\,000\,000] + \text{Tank cars} [3146 \times \$150\,000] = \$999,900,000$$



## Option 2

Pipeline investment costs can be split into four main categories: materials, labour, right-of-way fees and miscellaneous. Pipeline planners are hesitant to give a generalised estimation for pipeline construction cost because it is very dependent on the four variables mentioned as well as the location. For this reason a table developed by Parker (Parker, 2004), which incorporates a study on several models and 893 petroleum pipeline projects, was utilised. Table 4 in Appendix A shows that the median cost **for a 24" pipeline** is \$1,210,092.00 per km. This incorporates the sum of the four main categories of pipeline investment costs. Thus, the total investment cost of the pipeline is calculated as the cost per kilometre multiplied by the length of the route:

$$\text{\$1,210,092.00 / mile / 1.609 km} \times 1043 \text{ km} = \text{\$784, 416, 380}$$

## Option 3

This pipeline route runs along the coast and does not have to climb up to the same altitude as Gauteng and, thus, can be operated at a lower pressure. At a lower pressure, the pipeline does not have to have as thick a wall thickness as the one in option 3. Wall thickness is a major contributor to the cost of a pipeline. Therefore, the median cost of a **20" pipeline from Table 4 was chosen for this route** (Parker, 2004) . The total cost was calculated as follows:

$$\text{\$1055, 529.00 per mile / 1.609 km} \times 790 \text{ km} = \text{\$518 ,252, 274}$$



A basic verification on the accuracy of these figures can be checked against a pipeline project currently under way in South Africa and Mozambique. The ROMPCO Loop Line 2 gas pipeline project was at the time of writing under construction. The purpose of the pipeline is to deliver natural gas from the Temane fields in Mozambique to Gauteng. The pipeline is 127 km long and the project is billed at roughly R2 billion. This translates to a cost per kilometre of \$1,221,001.22 at the exchange rate at the time of writing (ROMPCO 2015). This gives a similar current real world example which certifies the cost figures used.

#### Option 4

The capital costs of fuel ships vary with size. Generally, the cost per m<sup>3</sup> of storage capacity for a ship reduces as the ship size increases. Table 10 in Appendix A indicates that for a ship capacity of around 135 000 m<sup>3</sup>, the cost will be around 170 million dollars. The capacity for the Transnet MPP is 1000 m<sup>3</sup>/h, as previously stated, which is 24 000 m<sup>3</sup>/day (IGT, 2015). The turnaround time for a ship transporting fuel from Coega to Durban is estimated to be around six days. A 135 000m<sup>3</sup> capacity ship will just fall short of this demand at 22,500 m<sup>3</sup> for six days. It was, therefore, decided that two 135 000 m<sup>3</sup> capacity ships should be utilised for this route option. This not only surpasses demand, it also creates a redundancy in the supply chain, in the case of one ship being out of service for maintenance or any other unforeseen problems. Additional loading and offloading infrastructure would be required at each harbour; this was estimated to be \$100 000 000. Therefore, the capital expenditure for two fuel ships was calculated as follows:

$$2 \times \$170\,000\,000 + \$100\,000\,000 = \$440,000,000$$



## Operation and Maintenance Cost

The annual operational and maintenance (O&M) costs for each mode were retrieved from the UK MARKEL energy model (Dodds and Mcdowal, 2012). Fuel and electricity costs are found to be marginal cost inputs in this model and are included with the overall fixed operational and maintenance costs. These values are plotted as a function of the fixed investment costs. Using these percentage functions provided by the model (Table 11, Appendix A), the operational and maintenance costs for each option were given as follows:

- **Option 1** – Rail Transportation annual O&M costs is given as 20% of fixed investment costs
- **Option 2** – Annual pipeline O&M is given as 5%
- **Option 3** – Annual pipeline O&M is given as 5%
- **Option 4** – Annual O&M costs for shipping are given as 5%

## Environmental:

The two environmental indicators assessed for this analysis was the amount of CO<sub>2</sub> emissions each option emitted and the amount of land use each option required. Other environmental options that were considered were sulphur dioxide emissions and noise pollution. There was, however, not enough reliable information available for such indicators.



## CO<sub>2</sub> emissions

Values for CO<sub>2</sub> emissions for freight ship and train transportation were obtained from a comprehensive data base established by the Network for Transport Measures (NTM, 2015). The figures are presented as grams per ton kilometre.

### Option 1

The emissions provided for Diesel freight train transportation is given as **21 g** per ton of cargo transported per kilometre (NTM, 2015).

### Option 2 & 3

Most pipeline pump stations and compressors run on electricity. CO<sub>2</sub> equivalent data is provided in grams of CO<sub>2</sub> per kilowatt hour and was extracted from a comprehensive greenhouse gas study on a selection of similar pipelines around the world. The average equivalent CO<sub>2</sub> emission for a 600mm diameter trans-country pipeline is given as 0.83 kg per kilowatt hour CO<sub>2</sub> (GHG). These emissions were based on a standard pump station with 70 kW pumps. It is assumed that the flow rate of these new pipelines will be similar to that of the MPP, which is designed at 1000 cubic meters per hour (Transnet, 2014). In order to equate this to grams per ton per kilometre, as the standard unit of measurement, the average velocity of the pipe was calculated in order to determine how quickly a ton of product takes to travel a kilometre. Therefore, we can calculate the equivalent CO<sub>2</sub> emissions per ton per kilometre as follows:

Velocity = Flow rate / Cross sectional area of pipe =

$$\frac{1000m^3}{\frac{\pi \times D^2}{4}}$$



Velocity = 3538 m/hour

= 0.983 m/s

It takes 1000 seconds for a ton of product to travel a kilometre = 16.6 minutes / km

Therefore equivalent CO<sub>2</sub> emissions = 0.83 kg/ kWh / 3.61

= **22.9 g**

#### Option 4

The CO<sub>2</sub> emissions provided for freight shipping is given as **10 g** per ton of cargo transported per kilometre (NTM, 2015). Another issue with shipping is the possible spillage of oil and other harmful waste into the ocean.

#### Land use

Land use is a major environmental indicator for large infrastructure projects. The ecological footprint of a project can have varying degrees influence on the local environment. This degree of influence depends on the size and spatial configuration of the project which can impede or damage ecological resources within its footprint (Jeroen *et al.*, 2013). For this study, the total land use in square meters for each project was used as a quantitative indicator.

#### Option 1

As it is assumed that this scenario would utilise existing railway lines, the land use for option 1 will be negligible compared to other options. Therefore, the total land use for this option will be given as **40 000 m<sup>2</sup>** for related service buildings for this system.



#### Option 2

600mm pipeline servitude of this nature would be required to be around 30 meters wide.

This is in order to allow for Safety borders, construction vehicles and future maintenance (ROMPCO, 2015). The total estimated land use can then be calculated as:

$$30 \text{ m wide servitude} \times 1043 \text{ km long} = \mathbf{31\,290\,000 \text{ m}^2}$$

#### Option 3

This option will utilise the same servitude width as that of Option 2. Therefore, the total land area can be calculated as:

$$30\text{m wide servitude} \times 790 \text{ km long} = \mathbf{23\,700\,000 \text{ m}^2}$$

#### Option 4

Shipping fuel requires loading and offloading piers that have to be constructed on a coastal shore or in a harbour. Although the total land area used will be far smaller than that of a pipeline or railway, the land being utilised for the facility is usually in a sensitive marine environment as opposed to many kilometres of pipeline servitude on the side of a road or through a commercial farm. Therefore, for this reason, the land use will be given a slightly higher figure in order to compensate for the sensitive environment. Using Google earth, a standard fuel offloading pier in Durban harbour requires 32 000 m<sup>2</sup>. This would be required at Coega and Durban harbour. Therefore, the total land area can be calculated as:

$$32\,000 \text{ m}^2 \times 2 \times 2 \text{ (sensitive marine environment factor)} = \mathbf{128\,000 \text{ m}^2}$$



## Social:

Social decision points are usually highly subjective criteria. There is no way of calculating or determining accurate figures for these criteria without a comprehensive survey and research team working on the case study. Thus, in order to assess the criteria, a scorecard was set up which allows the subjective allocation of a scores for each criterion. Each criterion was allocated a score out of 100 for each decision option. This scoring range was chosen in order to be consistent with the normalisation ratio that has been applied to the qualitative performance values. Certain subjective reasoning and study material was utilised in order to allocate the scores (Amos, 2009). The resultant margin of error with this form of scoring will be addressed with the stochastic simulation further on in this paper. The stochastic simulation will provide a quantitative sensitivity analysis for these figures.

### Option 1 – Transporting the fuel by existing Rail

Option 1	Score
Safety	82
Social acceptability	70
Job creation	85
Social Benefits	70
Alignment to strategic plans	80

Transporting liquid freight by rail is generally far safer than road transportation. There are few **recorded incidences of actual liquid fuel tanker accidents on South Africa's rail**. There have, of course, been a fair amount of general rail accidents resulting in several deaths over the years. A look at Table 12 in Appendix A, shows a comprehensive comparison of external social and environmental costs between heavy truck haulage and freight rail (Amos, 2009).



Option 2 – Transporting the fuel by a new pipeline from Coega to Gauteng

<b>Option 2</b>	<b>Score</b>
Safety	90
Social acceptability	70
Job creation	70
Social Benefits	60
Alignment to strategic plans	92

Pipeline accidents during operation are rare and no recordable incidents could be found in South Africa. There are, however, rare cases of deaths due to explosions of gas pipelines which have been tampered with in other parts of the world.

Cross country pipelines are fairly non-intrusive on local communities. Most pipelines are placed underground and the topsoil is replaced. They also tend to run across reserved servitudes and, if land has to be procured, then a compensation process is undertaken. Pipelines also tend to have offtakes at certain intervals which can supply fuel to local areas which had previously been undersupplied. This impacts positively on communities, especially since fuel is a major consumable of all LSM groups in South Africa. Building a pipeline fulfils an important part of the national strategic plans. The Energy Security Master Plan specifically calls for a pipeline to be built in order to secure future energy supply (DME, 2007). This pipeline would also run in close proximity to potentially large shale gas reserves in the Karoo basin (Map 01). This route would therefore, add an extra strategic advantage for ensuring energy security for Gauteng and South Africa.

Option 3 – Transporting the fuel by developing a new pipeline from Coega to Durban



<b>Option 3</b>	<b>Score</b>
Safety	90
Social acceptability	70
Job creation	68
Social Benefits	50
Alignment to strategic plans	75

The safety and social acceptability aspects of Option 4 are the same as those of Option 3. The job creation score is slightly lower due to the fact that the pipeline is shorter and, thus, would require less man hours to complete. Once operating, however, the amount of jobs required to work on the pipeline will be very similar to the longer route. The pipeline in Option 4 also aligns to strategic plans in the same manner as Option 3.

Option 4 – Transporting the fuel by ship from Coega to Durban

<b>Option 4</b>	<b>Score</b>
Safety	75
Social acceptability	70
Job creation	85
Social Benefits	60
Alignment to strategic plans	95

Although ships do not pose any serious safety risks to the general public, there is much recorded and anecdotal evidence of injuries and fatalities aboard large freight ships. These vessels are, essentially, moving petroleum plants which travel over rough seas. There will always be risks involved in such environments. The South African coastline is already heavily trafficked with large



freight ships. There does not seem to be any record of mass protestation against this and social acceptability should be adequate. The potential for job creation in the shipping industry is immense. South Africa does not have a single vessel register to its (sovereign naval registry). Ship building and repair is a main strategic goal aligned with the government’s National Development Plan. The main plan comes in the form of Operation Phakisa. Operation Phakisa focuses on developing the oceans economy and states that between 800 000 and 1 000 000 jobs can be created by 2033 (Operation Phakisa, 2014).

**Stage 8 – Application of the Ranking Methodology (or Aggregation Technique)**

**Summary of Performance Values**

	Option 1	Option 2	Option 3	Option 4
<b>Technical :</b>				
Energy Efficiency (%)	89	95	95	96
Flexibility	72	52	52	61
<b>Economic:</b>				
Investment cost (\$)	999900000	784416380	518252274	440000000
Operation and maintenance costs (%)	20	5	5	5
<b>Environmental:</b>				
CO <sub>2</sub> emissions (g)	21	23	23	10
Land use (Sq m)	40000	31290000	23700000	128000
<b>Social:</b>				
Safety	82	90	90	75
Social acceptability	70	65	65	70
Job creation	85	70	68	85
Social Benefits	70	50	50	60
Alignment to strategic plans	80	75	75	90

Table 1: Summary of Performance Values



## Normalisation and Weighted Sum Calculation

In order to ensure that the performance values of each criterion could be compared relevantly, a common internal scale was established. This was done mathematically by utilising a value function. More specifically, an additive model on the criteria was applied using a simple linear scale from 0 to 100. This was done for all performance values in order to ensure that we could compare **“apples with apples” across different** criteria (DTU, 2014). For criteria where the desirable value is the higher one, the highest value was given a value of 100 and every other value scaled relatively. For criteria such as cost, where the desirable value is the lower value, the same linear scale was applied, however, with the weighting allocated as a negative. This negative allocation allows for the undesirable criteria to be accounted for appropriately in the weighted sum calculation. For purposes of efficiency in the weighted sum equation, the negative allocation was not assigned to each undesirable performance value, but rather its corresponding weighting. Table 2 indicates the outcome of the normalisation process on the performance values.



	Option 1	Option 2	Option 3	Option 4
<b>Technical :</b>				
Energy Efficiency (%)	93	99	99	100
Flexibility	100	72	72	85
<b>Economic:</b>				
Investment cost (\$)	100	78	52	44
Operation and maintenance costs (%)	100	25	25	25
<b>Environmental:</b>				
CO <sub>2</sub> emissions (g)	91	100	100	43
Land use (Sq m)	1	100	76	2
<b>Social:</b>				
Safety	91	100	100	83
Social acceptability	100	93	93	100
Job creation	100	82	80	100
Social Benefits	100	71	71	86
Alignment to strategic plans	89	83	83	100

Table 2 : Normalised table of performance values

With the performance values normalised on a suitable scale, the weighted sum calculation was performed. Table 3 below indicates the outcome of the weighted sum calculation for the normalised performance values. The table also includes a column for the allocated weighting of each performance criteria as well as the total weighted sum for each option in red.



	Option 1	Option 2	Option 3	Option 4	Weighting
<b>Technical :</b>					<b>0.25</b>
Energy Efficiency (%)	93	99	99	100	<b>0.125</b>
Flexibility	100	72	72	85	<b>0.125</b>
<b>Economic:</b>					<b>0.3</b>
Investment cost (\$)	100	78	52	44	<b>-0.15</b>
Operation and maintenance costs (%)	100	25	25	25	<b>-0.15</b>
<b>Environmental:</b>					<b>-0.15</b>
CO <sub>2</sub> emissions (g)	91	100	100	43	<b>-0.075</b>
Land use (Sq m)	1	100	76	2	<b>-0.075</b>
<b>Social:</b>					<b>0.3</b>
Safety	91	100	100	83	<b>0.06</b>
Social acceptability	100	93	93	100	<b>0.06</b>
Job creation	100	82	80	100	<b>0.06</b>
Social Benefits	100	71	71	86	<b>0.06</b>
Alignment to strategic plans	89	83	83	100	<b>0.06</b>
<b>Total</b>	<b>16</b>	<b>17</b>	<b>22</b>	<b>37</b>	

Table 3 : Normalised Table of Performance Values with Calculated Results of Weighted Sum

The results of Table 3 above show that Option 4, which proposes that the fuel be transported by ship from Coega to Durban Harbour and then on to the MPP, is the preferred choice. Option 3, which proposes that a new pipeline be built from Coega to Durban and then tie in to the MPP, came out as the second highest choice. Option 2, which proposes a pipeline from Coega direct to Johannesburg via Bloemfontein, came out as the third choice. Finally, Option 4 which proposes the transportation of liquid fuel from Coega to Johannesburg on new rail tankers, came out as the least preferred choice. Table 4 below provides a summary of the final outcome.



Ranking	Option	Title
1	4	Transporting the fuel by ship from Coega to Durban
2	3	Transporting the fuel by developing a new pipeline from Coega to Durban
3	2	Transporting the fuel by a new pipeline from Coega to Gauteng
4	1	Transporting the fuel by existing Rail from Coega to Gauteng

Table 4 : *Ranking of the options based on MCDA*



### 3. Stochastic Analysis

This stochastic analysis has been adopted in order to establish the variance of probable outcomes from the MCDA analysis. This is done by employing Monte Carlo Simulation (MCS) on the initial normalised performance rankings and weightings in the MCDA. By utilising the stochastic simulation, more information can be obtained on the robustness of the initial weighting and performance values. This ultimately provides a form of sensitivity analysis, which will indicate the likelihood of a different outcome in the analysis due to the variability of the performance values and weightings. This exercise, essentially, allows for a thorough assessment of the problem, without having to spend valuable resources on collecting first hand data over a long period of time.

The stochastic simulation also negates any irregularities, due to subjective data input in the decision making process. By simulating a broad range of possible inputs, the effects of subjective biasedness can be analysed individually, in order to determine each decision variables effects on the outcome of the MCDA process.

#### Monte Carlo Simulation

The MCS approach in this study involves repeated random sampling of each performance value and weighting in order to determine the robustness of the initial ranking order. This was done in five steps:

- Identify the mathematical model to be analysed
- Identify the variables



- Define the parameters for those variables
- Create random samples within those parameters
- Simulate and analyse output

The mathematical model for the performance score ( $S_i$ ), retrieved from the decision matrix with  $i$  columns and  $j$  rows, was identified as:

$$(S_i) = \sum_{j=1}^{11} x_{ij}w_j \quad i = 1,2,3,4$$

Where:  $x$  = performance value

$w$  = weighting

$i$  = column for each option

$j$  = row for each criteria

The parameters in this simulation were established by assigning upper and lower limits for each performance value and weighting. A random sample generator was employed to simulate values of  $x$  and  $w$  in the equation above. The range of these limits varies with the level of uncertainty of the particular performance value. A summary of these parameter limits are displayed in Table 5.



	Option 1	Option 2	Option 3	Option 4	Weighting
	Limits	Limits	Limits	Limits	Limits
	Lower ; Upper	Lower ; Upper	Lower ; Upper	Lower ; Upper	Lower ; Upper
Energy Efficiency (%)	90 ; 95	95 ; 100	95 ; 100	95 ; 100	5 ; 20
Flexibility	90 ; 100	70 ; 80	70 ; 80	90 ; 100	5 ; 20
Investment cost (\$)	90 ; 100	60 ; 85	60 ; 75	35 ; 50	15 ; 25
Operation and maintenance costs (%)	87 ; 93	22 ; 28	22 ; 28	22 ; 28	15 ; 25
CO <sub>2</sub> emissions (g)	85 ; 100	85 ; 100	85 ; 100	30 ; 55	0 ; 10
Land use (Sq m)	0 ; 5	95 ; 100	95 ; 100	0 ; 5	0 ; 10
Safety	85 ; 100	85 ; 100	85 ; 100	85 ; 100	0 ; 10
Social acceptability	85 ; 100	85 ; 100	85 ; 100	85 ; 100	0 ; 10
Job creation	90 ; 100	80 ; 95	80 ; 95	90 ; 100	0 ; 10
Social Benefits	90 ; 100	60 ; 80	60 ; 80	80 ; 100	0 ; 10
Alignment to strategic plans	85 ; 95	80 ; 95	80 ; 95	90 ; 100	0 ; 10

Table 5: List of Upper and Lower Limits Applied to Each Performance Criterion for Random Sample

Generation

MCS works most effectively based on the law of large numbers (Paltani, 2010), thus, over 10 000 random sample iterations were performed in order to ensure a comprehensive simulation. The total performance value (S<sub>i</sub>) was calculated for each iteration and tallied. The simulation was run using **the random number generator macro in Microsoft Excel™**. A portion of this simulation and the equations used are displayed in Appendix B of this paper.

Two outcomes of interest were analysed in order to determine the sensitivity and robustness of the initial ranking order. The first output analysed was the range and mean of the total performance values after 10 000 iterations for each option. The second output analysed was, a simple plot of the total win percentage that each option acquired after the simulation.



Figure 4 indicates the range of total performance values each option achieved after 10 000 iterations. The ranges for this simulation cover a relatively vast area of the table. This occurred due to the high variance allocated to the upper and lower limits of each performance criteria. This allowed the simulation to scrutinise a wide variety of scenarios based on any inaccuracies on the initial performance scores. The negative scores that appeared in the simulation occurred when a random combination of all negatively marked criteria was allocated high values and high weightings coupled with all positive values allocated low scores and weightings. Figure 4 also plots the average score for each option after the simulation. This provides a useful indicator that can be checked against the initial rank order.

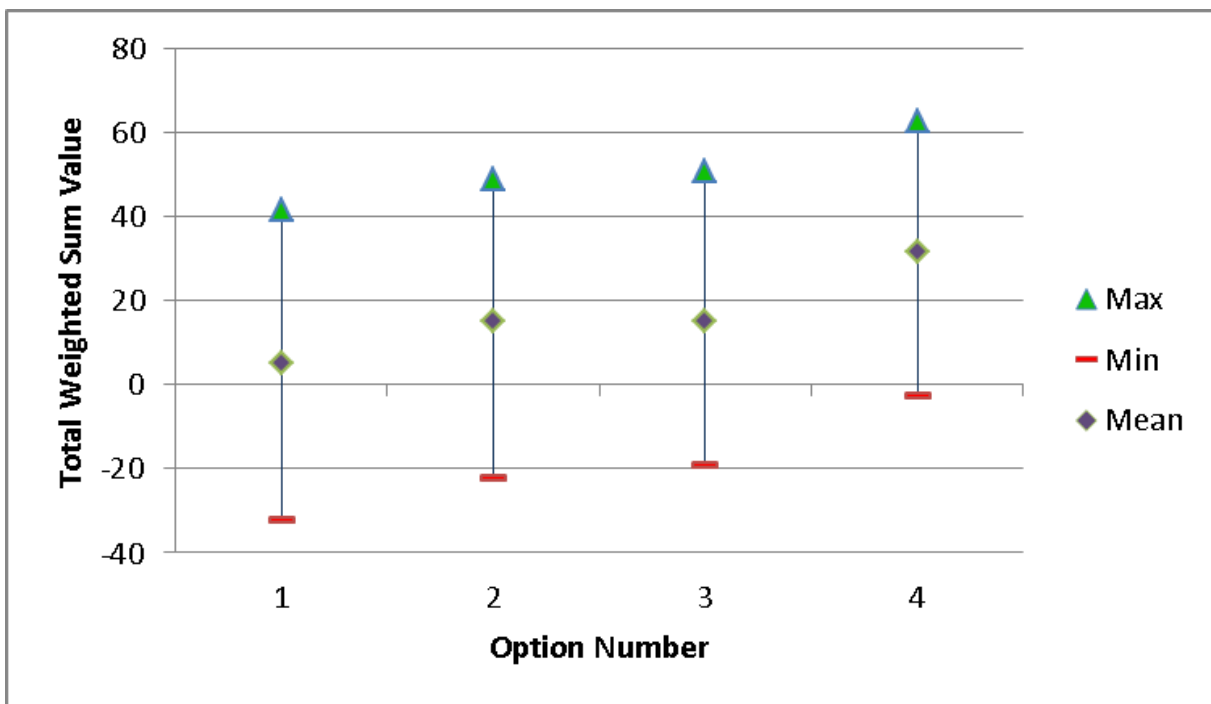


Figure 4 : Chart Indicating the Range of Total Weighted Sum of Performance Values After 10 000 Iterations of MCS



Figure 5 below indicates the proportion that each option comes first, after each iteration. Option 4 has come out of the simulation as the clear overall favourite with an 89.7% win rate after 10 000 iterations. Options 2 and 3 have come out of the simulation on an almost even par with 5.1% and 5.2%, respectively. Option 1 failed to come out of a single iteration as the preferred choice.

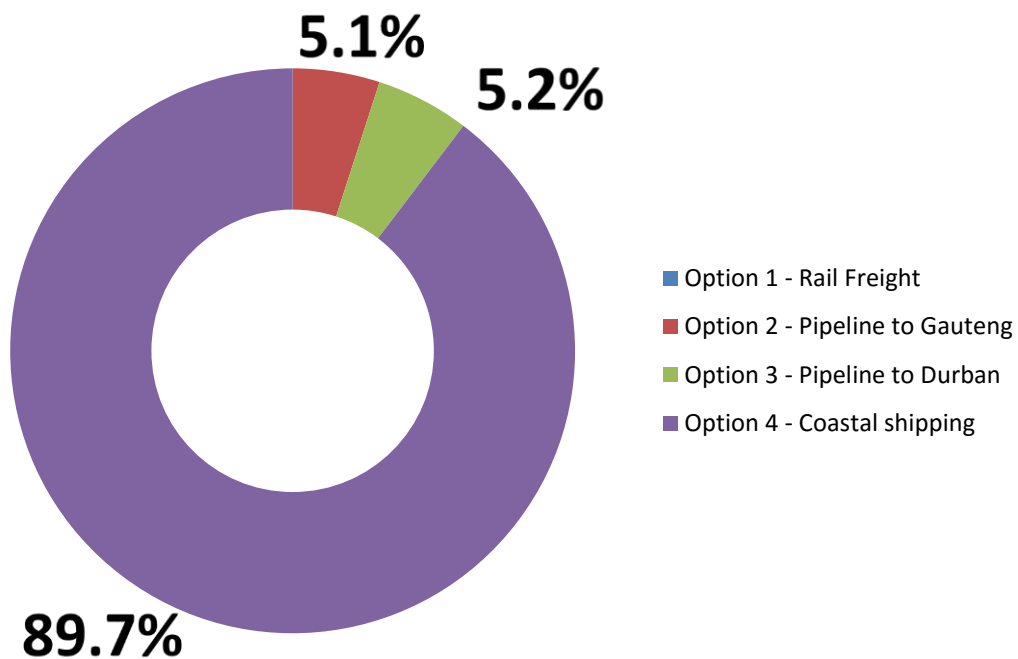


Figure 5: Chart indicating total win percentage of each option after 10 000 iterations

The overwhelming majority of win outcomes for Option 4 in the MCS, confirms the outcome of the initial MCDA results. A summary of the outcomes from the stochastic analysis are presented in Table 6 on the next page.



Ranking	Option	Title
1	4	Transporting the fuel by ship from Coega to Durban
2	3	Transporting the fuel by developing a new pipeline from Coega to Durban
3	2	Transporting the fuel by a new pipeline from Coega to Gauteng
4	1	Transporting the fuel by existing Rail from Coega to Gauteng

Table 6 : *Ranking of Options Based on Stochastic Analysis*



## 4. Analysis of Results

### 4.1 Analysis of the Case Study Results

The outcome of the MCDA case study clearly presents Option 4 as the dominant preference of the four choices. This is further reinforced by the stochastic simulation, which resulted in Option 4 receiving an overwhelming win percentage of 89.7%. One reason for this high score is the relatively low economic costs attributed to Option 4, compared to the other options. The economic criteria in this study were allocated a significantly large proportion of the weighting compared to other criteria. As the economic criteria were also allocated a negative weighting, it stands to reason that, an option with significantly lower economic costs stand a good chance over more expensive options. In fact, a clear correlation can be seen between the rank order of preferred options in this study and their corresponding economic criteria values. It can be seen that the ranked order of the options from the lowest investment cost to the highest investment cost, is the same as the ranked order of the most preferred option to the least preferred option, respectively.

Aside from strong economic performance of Option 4, this route also performed well in all other main criteria groups. Option 4 achieved the highest performance scores for three out of the five social criteria, as well as one of each of the technical and environmental criteria. This strong showing across the board for Option 4 contributed significantly to the dominate win percentage achieved in the MCS.

While it is not unusual for the economic cost criteria of a study like this to have the highest allocated weighting, the decision to allocate these criteria with the highest weighting is a subjective decision. The utilisation of the rank order weighting method of course recognises that certain criteria are more important than others, but it does not offer a precise measure of how to scale



weights objectively. The Monte Carlo Simulation was employed in order to negate the unavoidable subjectivity of allocating weightings in this method, however, the upper and lower random sample limits in the simulation are also allocated with a certain amount of subjectivity. Figure 6 below offers a comparison between the original MCDA results and the MCS results.

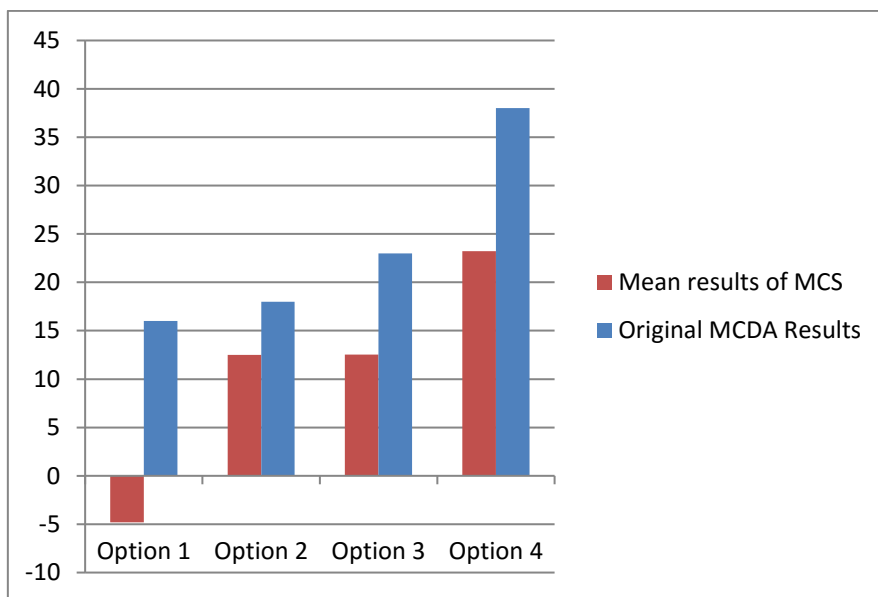


Figure 6: Comparison of original MCDA score results vs mean MCS score

The average scores presented by the MCS for Options 2 and 3 were very close, at 12 and 13, respectively. The ranking order of MCS results for these options correlates with the rank order of the original MCDA analysis, with Options 2 and 3 scoring 17 and 22, respectively. Although the rank orders for the two studies correlate, the ratios of the results between the two studies do not. This indicates a slight discrepancy in the preference scoring between the MCDA and MCS. The comparison of these ratios is presented in Table 7.



	<b>MCS Mean Results</b>	<b>MCDA Results</b>	<b>Ratios</b>
<b>Option 1</b>	-5	16	<b>0.31</b>
<b>Option 2</b>	12	17	<b>0.69</b>
<b>Option 3</b>	13	22	<b>0.59</b>
<b>Option 4</b>	23	37	<b>0.62</b>

**Table 7:** Table Showing Variable Ratios between Mean MCS Results and Original MCDA Results

At a ratio of 0.69 and 0.59 and 0.62 for Options 2, 3 and 4, respectively, the preference scoring between are presented as slightly different, albeit with a relatively small margin of error. This small margin of error indicates that the outcome of the MCS is reliable for these values but, perhaps, indicates that there may be some elasticity with the simulation.

The difference in scores for Option 1 presents an anomaly where the mean MCS result is a negative number at -5. This negative figure occurs in iteration where the random sample generator allocates all negatively weighted performance values with the higher end values in the range and all positively weighted performance values with lower end figures in the range. Despite these slight discrepancies, it is overwhelmingly clear that, after 10 000 iterations of the Monte Carlo Simulation, the rank order of the MCDA performance results are confirmed.

#### 4.2 Limitations and Shortcomings of the Analysis

The application of stochastic analysis in the MCDA has proved to be an adaptable and multi-faceted tool. The simulation of random variable samples, within specified ranges, greatly enhances the scope of the MCDA, while presenting a reliable sensitivity mechanism. However, a key



shortcoming to this characteristic is that the qualitative ranges set for each performance value still require a reliable base value to be set as a datum. This original base value would need to be established reliably with, at least, an initial level of research on each performance criteria, as performed in this study. Thus, if a serious mistake is committed during the initial establishment of the base values, the entire simulation could be compromised. This same notion applies to the weighting method. If the weighting method is established subjectively, then this will, in turn, compromise the objective nature of the simulation.

It is also important to note that the specified limit range for each random number generator is not based on a subjective view point in terms of preference. The limit ranges are, rather, based on the degree of uncertainty obtained for each performance value. This is a double edged sword as, by varying the ranges of each performance value, the outcome of the win percentages can be skewed.

#### **4.3 Conclusion from the Case Study**

The MCDA and MCS both indicate that shipping the fuel from Coega to Durban and then utilising the Transnet MPP is the clear favourite. The building of new pipelines on route Options 2 and 3 have very similar scores and both can be considered with further research and analysis. An interesting outcome from the study is that the top two preferred options, namely, coastal shipping and a pipeline to Johannesburg, correlate with the two final options that PetroSA has considered for its detailed study. This outcome provides vindication for the PetroSA decision, as well as the integrity of the MCDA in this study. Furthermore, It is clear that, with an overall win percentage of 89.7%, the option of establishing a shipping route from the Project Mthombo refinery at Coega, to the MPP at Durban, should be the preferred business case for PetroSA .



## 5. Conclusion

It is clear from this study that the planning of liquid fuel transportation networks involves many variable parameters. The make-up of a given network can vary widely from option to option. In order to plan a system that transports fuel from an origin to a destination, the decision maker can be faced with options that vary dramatically from, subterranean high pressure pipe lines, to sophisticated deep sea tankers. There is, evidently, a wide range of deep knowledge and expertise required in order to develop a thorough and relevant decision model for such systems. The comprehensive research and data collection would not only be expensive and time consuming, but would have to be clarified and confirmed by various discipline experts. The fundamental variability of the make-up of these systems, as well as the subsequent data, may leave questions of uncertainty with various decision makers. By incorporating a stochastic analysis into the MCDA model, this uncertainty can be mitigated substantially.

The MCDA model in itself has proven to be a valuable method for analysing a relatively complex liquid fuel distribution problem. The format of the MCDA process significantly simplifies the magnitude of the study. The results, which are conveniently presented on the MCDA table, give an instant and clear picture of the decision problem. This is a significant attribute for liquid fuel projects, which involve an array of stakeholders who all have their own interests. The MCDA not only supports the principles of stakeholder engagement, but also presents its results in a manner that can instantly be understood by all. Large projects, such as the one in this case study, invariably hold certain controversies amongst certain stakeholders. The MCDA can help polarised stakeholders to understand each **other's problems and reach a compromised solution**. Traditional studies, such as a cost- benefit analysis, tend to be long winded and complicated to understand.



The MCDA is not only easier to understand but provides a holistic approach to the problem by attributing each decision criteria with its relevant unit of measurement. The CBA approach, which monetises all criteria, falls short of the relevant consideration that MCDA can provide for each performance criteria. The positive analysis format of the MCDA is further enhanced by the incorporation of a stochastic analysis.

In an industry where consultants charge by the hour for supplying research reports, the time required in order to perform a relevant study is directly proportional to the cost of that study. Thus, any time savings that the MCDA reinforced with a stochastic analysis can save, will not only reduce lead times, but also significantly reduce the cost of that study. In addition to time savings, this method of analysis can reduce the need for detailed field research. This is a positive attribute for studies in liquid fuel transportation where the complexities already alluded to in this report, are vast and complex. A practical application for this method could be in a situation where a decision making entity has analysed a high level pre- feasibility study for a proposed project and needs to make a decision on whether to move forward with the detailed feasibility and how. If the options vary as drastically as the ones in this case study, then a detailed feasibility study would require an immense amount of intellectual and financial resources in order to provide a reliable result. The stochastic simulation coupled with the MCDA could be incorporated into the pre-feasibility study. The analysis could eliminate the unlikely decision options and indicate which ones are the most feasible, just as demonstrated for the case study in this thesis. With a relatively fast simulation process, the decision makers can narrow down which options to focus on and, thus, drastically reduce the amount of time and resources required to complete a detailed feasibility study. Overall, the MCDA and stochastic analysis employed in this case study has proved to be a versatile and robust tool that can aid in the analysis of liquid fuel transportation problems.



## 6. Recommendations

- A clear point of interest for this study would be to compare the results of this paper, to those of the official feasibility study for the Project Mthombo Refinery, once released. Clear comparisons could be made on the route option chosen and the decision methods for those options. Another significant comparison could be between the different criteria values obtained by each study, as well as, an assessment on how the stochastic simulation is able to mitigate discrepancies in such values.
- A significant pronouncement in this study was the decision to omit road freight from the analysis. This omission was wholly justified in the paper, however, it would be highly useful to include road freight in a study like this in order to compare values which influence policy direction and decision making.



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## 8. Appendix A – Figures Used for Developing Performance Values in the MCDA Process

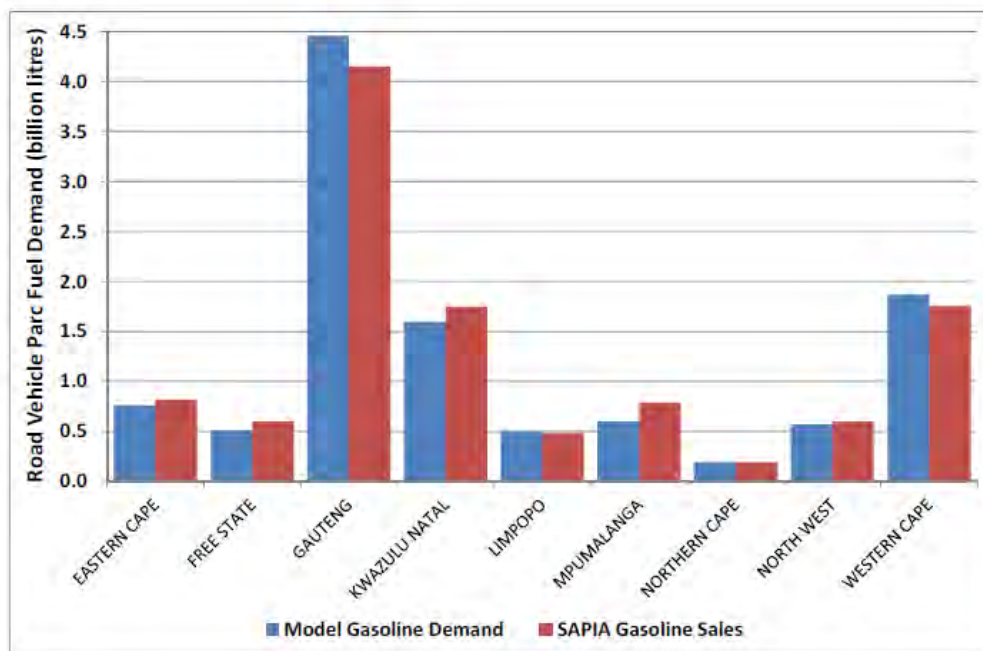


Figure 7: Model Gasoline Consumption vs Actual Gasoline Consumption (Mervan et al , 2012)

Diameter (m)	Throughput (kg d-1)	Operations energy efficiency	Total investment cost (EU(€2000) (kg d-1)-1)	Total investment cost (EU€m(2000) km-1)	UK MARKAL investment cost (GB£(2000) GJ-1 y-1)
0.08	2,143	99%	53,681	0.23	630
0.23	21,429	100%	12,369	0.53	145
0.30	21,429	100%	14,467	0.63	170
0.36	21,429	100%	19,367	0.83	227
0.23	214,286	77%	1,311	0.56	15
0.30	214,286	95%	1,464	0.63	17
0.36	214,286	98%	1,946	0.83	23
2.00	9,000,000	93%	133	2.39	2

Table 8. Investment Costs and Energy Efficiencies for 500 km Pipelines of Varying Sizes and Throughputs. Original Data from Krewitt and Schmid (2004).



Pipe dia.	Materials*	Labor*	Misc.*	Right of Way*	Total*
4" mean median %	\$60,017/mi	\$268,585/mi	\$101,668/mi	\$56,222/mi	\$486,492/mi
	\$30,570/mi 15%	\$232,980/mi 45%	\$63,414/mi 21%	\$38,301/mi 19%	\$364,523/mi
6"	\$57,863/mi	\$239,916/mi	\$115,264/mi	\$54,364/mi	\$467,407/mi
	\$46,086/mi 16%	\$182,299/mi 52%	\$65,610/mi 23%	\$36,519/mi 9%	\$333,601/mi
8"	\$93,436/mi	\$208,658/mi	\$139,034/mi	\$36,947/mi	\$478,076/mi
	\$55,278/mi 22%	\$146,203/mi 42%	\$85,832/mi 28%	\$26,011/mi 8%	\$306,925/mi
10"	\$102,258/mi	\$246,771/mi	\$110,033/mi	\$43,427/mi	\$503,489/mi
	\$70,143/mi 21%	\$196,864/mi 49%	\$78,635/mi 22%	\$46,461/mi 8%	\$456,532/mi
12"	\$113,981/mi	\$404,051/mi	\$174,573/mi	\$63,389/mi	\$755,993/mi
	\$88,484/mi 19%	\$282,404/mi 51%	\$116,931/mi 22%	\$45,045/mi 8%	\$542,862/mi
16"	\$150,324/mi	\$407,615/mi	\$214,930/mi	\$82,542/mi	\$855,411/mi
	\$112,673/mi 23%	\$271,033/mi 44%	\$109,505/mi 25%	\$34,895/mi 8%	\$563,564/mi
20"	\$210,178/mi	\$491,082/mi	\$273,170/mi	\$81,100/mi	\$1,055,529/mi
	\$170,895/mi 23%	\$410,323/mi 47%	\$169,583/mi 23%	\$29,422/mi 7%	\$800,835/mi
24"	\$245,372/mi	\$574,579/mi	\$297,635/mi	\$99,112/mi	\$1,210,092/mi
	\$222,211/mi 26%	\$425,559/mi 48%	\$174,313/mi 20%	\$21,091/mi 6%	\$869,293/mi
30"	\$395,461/mi	\$637,608/mi	\$349,755/mi	\$86,631/mi	\$1,469,456/mi
	\$372,276/mi 30%	\$487,461/mi 42%	\$276,557/mi 23%	\$55,006/mi 5%	\$1,163,462/mi
36"	\$519,622/mi	\$764,100/mi	\$398,088/mi	\$86,900/mi	\$1,768,710/mi
	\$464,440/mi 31%	\$710,704/mi 42%	\$318,414/mi 22%	\$52,636/mi 5%	\$1,575,905/mi
42"	\$713,651/mi	\$998,242/mi	\$492,774/mi	\$96,377/mi	\$2,301,044/mi
	\$641,272/mi 35%	\$861,204/mi 41%	\$372,439/mi 20%	\$62,253/mi 4%	\$1,977,644/mi

\*all costs in year 2000 dollars

Table 9 – Cost of Petroleum Pipelines Per Mile Over Different Diameters. (Extracted from Parker 2004)

Size m <sup>3</sup>	CAPEX million \$	CAPEX thousand \$ per m <sup>3</sup>	Typical crew number	Typical harbor cost (Europe)
215.000	250	6	30 - 35	100 – 200k\$ per visit
135.000	170	6.5	25 - 35	75 – 150k\$ per visit
28.000	80	15	15 - 20	25 - 40k\$ per visit

Table 10 – Typical Investment Cost for Fuel Ships. Extracted from (IGU, 2015)



Technology	Size	Fixed O&M (% of investment costs)	Fixed O&M costs		
			2000	2025	2050
Liquefaction	Large	7%	1.1	0.4	0.4
Liquefaction	Medium	7%	1.1	0.7	0.7
Ship	Large	5%	0.4	0.2	0.2
Road tanker	Small	20%	0.8	0.8	0.8
Tube trailer	Small	20%	3.2	3.2	3.2
Pipeline	All	5%	N/A	N/A	N/A
LH <sub>2</sub> -LH <sub>2</sub> fuelling station	All	5%	0.5	0.4	0.3
LH <sub>2</sub> -GH <sub>2</sub> fuelling station	All	5%	0.8	0.6	0.5
LH <sub>2</sub> -GH <sub>2</sub> fuelling station	All	5%	0.6	0.5	0.4
GH <sub>2</sub> distributed fuelling station	All	5%	1.5	0.9	0.7

Table 11 – Recommended UK MARKAL Annual Fixed O&M Costs Data for Different Transportation Technologies (Extracted from Dodds & Mcdowal, 2012)

Figure 5-2: External cost estimates (EU)

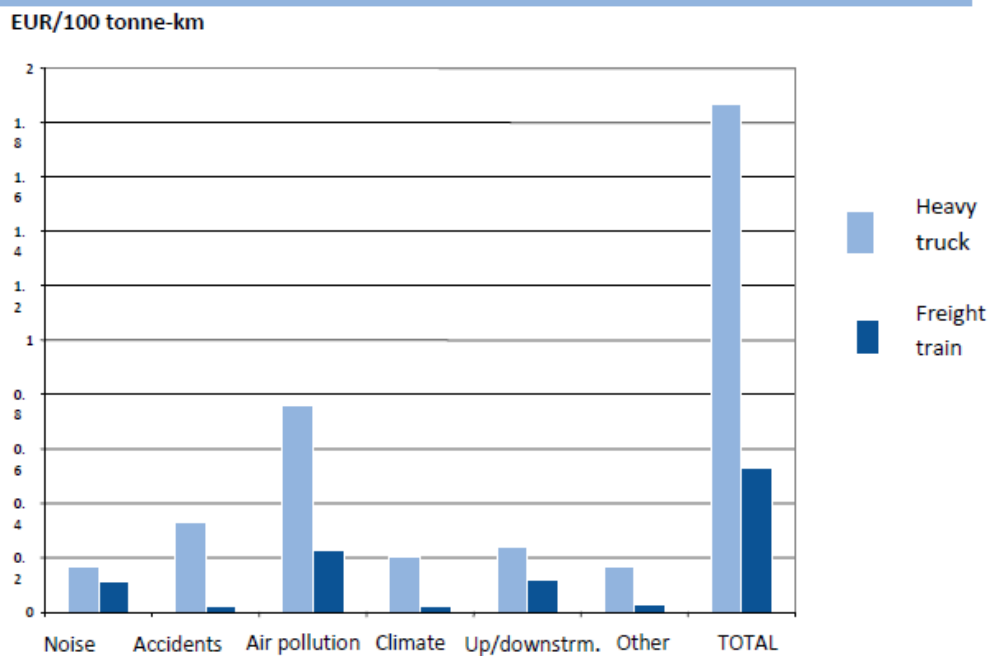


Table 12 – External cost estimates of heavy truck and freight train haulage (Extracted from Dodds & Mcdowal, 2012)



## 9. Appendix B – Developed Spreadsheets Showing the Iteration process of the Monte Carlo Simulation

*Note: The MCS spreadsheets developed for simulating certain performance values have been presented with a maximum of 60 iterations. It was not feasible to print the entire work book with 10 000 iterations.*

*The spreadsheets were developed for each performance criteria but only a few are presented for the sake of saving paper.*

*Table 5 below provides an overview of the upper and lower limits applied to the MCS equation for each performance criteria. The upper and lower limits are also presented in the few examples presented.*

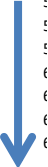
**Table 5:** List of Upper and Lower Limits Applied to Each Performance Criterion for Random Sample Generation

	Option 1	Option 2	Option 3	Option 4	Weighting
	Limits	Limits	Limits	Limits	Limits
	Lower ; Upper	Lower ; Upper	Lower ; Upper	Lower ; Upper	Lower ; Upper
Energy Efficiency (%)	90 ; 95	95 ; 100	95 ; 100	95 ; 100	5 ; 20
Flexibility	90 ; 100	70 ; 80	70 ; 80	90 ; 100	5 ; 20
Investment cost (\$)	90 ; 100	60 ; 85	60 ; 75	35 ; 50	15 ; 25
Operation and maintenance costs (%)	87 ; 93	22 ; 28	22 ; 28	22 ; 28	15 ; 25
CO <sub>2</sub> emissions (g)	85 ; 100	85 ; 100	85 ; 100	30 ; 55	0 ; 10
Land use (Sq m)	0 ; 5	95 ; 100	95 ; 100	0 ; 5	0 ; 10
Safety	85 ; 100	85 ; 100	85 ; 100	85 ; 100	0 ; 10
Social acceptability	85 ; 100	85 ; 100	85 ; 100	85 ; 100	0 ; 10
Job creation	90 ; 100	80 ; 95	80 ; 95	90 ; 100	0 ; 10
Social Benefits	90 ; 100	60 ; 80	60 ; 80	80 ; 100	0 ; 10
Alignment to strategic plans	85 ; 95	80 ; 95	80 ; 95	90 ; 100	0 ; 10



Table 13 – Developed spreadsheet for performing MCS for Energy Efficiency performance criteria

Iteration No.	Limits ; Upper 90 ; 95	Lower Limits ; Upper 95 ; 100	Lower Limits ; Upper 95 ; 100	Lower Limits ; Upper 95 ; 100	Lower Limits ; Upper 95 ; 100	Lower Limits ; Upper 95 ; 100
	ENERGY EFFICIENCY 1	ENERGY EFFICIENCY 2	ENERGY EFFICIENCY 3	ENERGY EFFICIENCY 4	WEIGHTING 1	
1	94	99	96	99	0.15	
2	90	96	98	96	0.13	
3	95	100	96	96	0.18	
4	92	98	100	96	0.06	
5	90	95	100	99	0.16	
6	94	99	98	95	0.1	
7	92	100	98	97	0.1	
8	91	97	96	97	0.15	
9	91	95	96	95	0.08	
10	93	95	97	95	0.13	
11	91	99	95	100	0.08	
12	95	100	98	95	0.14	
13	95	96	96	95	0.08	
14	95	100	100	100	0.13	
15	93	99	97	100	0.12	
16	90	99	98	98	0.12	
17	91	99	97	99	0.19	
18	90	98	98	96	0.1	
19	90	100	95	96	0.15	
20	95	95	95	95	0.09	
21	95	98	99	95	0.14	
22	91	96	96	100	0.17	
23	91	96	100	97	0.16	
24	91	96	96	96	0.12	
25	92	97	99	98	0.19	
26	92	99	98	96	0.08	
27	93	97	97	97	0.06	
28	94	96	96	96	0.15	
29	90	97	99	100	0.07	
30	91	100	97	95	0.15	
31	92	96	95	100	0.05	
32	93	99	96	100	0.18	
33	93	100	99	98	0.17	
34	90	95	98	95	0.1	
35	92	98	98	98	0.09	
36	93	100	96	97	0.16	
37	91	96	97	100	0.11	
38	92	95	99	95	0.15	
39	94	95	100	99	0.08	
40	91	95	95	100	0.09	
41	93	98	95	98	0.12	
42	91	100	96	97	0.1	
43	95	97	99	100	0.2	
44	93	98	98	96	0.15	
45	92	96	100	100	0.08	
46	92	100	98	100	0.16	
47	94	100	96	98	0.08	
48	95	97	98	99	0.16	
49	90	99	97	96	0.07	
50	92	98	97	96	0.13	
51	90	100	100	100	0.06	
52	93	98	96	96	0.15	
53	92	99	99	98	0.08	
54	95	100	98	99	0.11	
55	95	100	99	97	0.1	
56	94	95	99	100	0.16	
57	94	95	100	99	0.16	
58	94	95	98	98	0.11	
59	94	95	95	100	0.17	
60	94	95	96	96	0.09	
61	94	95	99	97	0.2	
62	94	95	100	96	0.12	
63	94	95	96	96	0.07	



Random sample generation to  
10 000 iterations



Table 14 – Developed spreadsheet for performing MCS for the flexibility performance criteria

Iteration No.	Limits Lower ; Upper	Limits Lower ; Upper	Limits Lower ; Upper	Limits Lower ; Upper	Limits Lower ; Upper
	90 ; 100	70 ; 80	70 ; 80	90 ; 100	5 ; 20
	FLEXIBILITY 1	FLEXIBILITY 2	FLEXIBILITY 3	FLEXIBILITY 4	WEIGHTING
1	91	72	73	98	0.06
2	91	78	74	92	0.07
3	98	74	76	99	0.14
4	100	75	78	90	0.17
5	99	74	73	99	0.17
6	99	74	80	97	0.15
7	94	73	71	96	0.11
8	93	77	80	97	0.08
9	92	70	74	98	0.12
10	91	73	76	93	0.14
11	91	74	75	92	0.07
12	91	79	80	97	0.1
13	94	72	74	100	0.07
14	93	80	76	91	0.08
15	94	77	80	99	0.11
16	97	80	73	98	0.06
17	91	78	78	99	0.05
18	97	75	78	93	0.13
19	93	80	78	100	0.07
20	91	78	79	91	0.08
21	96	73	78	92	0.17
22	96	76	77	98	0.15
23	98	70	77	95	0.08
24	91	80	80	93	0.16
25	92	71	72	92	0.2
26	98	71	71	100	0.17
27	92	72	78	99	0.15
28	90	72	79	96	0.17
29	92	80	71	99	0.12
30	96	74	80	91	0.17
31	96	79	78	99	0.11
32	100	76	72	91	0.11
33	100	78	80	92	0.18
34	97	71	75	92	0.2
35	93	73	70	95	0.16
36	90	73	73	93	0.13
37	90	70	75	92	0.2
38	99	78	77	92	0.12
39	98	76	76	92	0.14
40	96	77	77	95	0.08
41	90	77	76	95	0.1
42	90	80	79	95	0.06
43	96	79	80	97	0.17
44	90	71	72	97	0.13
45	91	78	78	90	0.1
46	93	79	78	94	0.11
47	95	76	76	94	0.05
48	98	72	70	95	0.05
49	93	72	71	98	0.14
50	92	76	78	100	0.1
51	92	73	73	91	0.15
52	95	79	75	91	0.17
53	92	76	78	91	0.19
54	90	79	74	94	0.2
55	97	78	77	96	0.07
56	96	79	77	98	0.17
57	91	78	74	90	0.16
58	91	79	71	96	0.17
59	95	73	71	97	0.16
60	--	--	80	91	0.07
61			70	97	0.13
62			72	94	0.15
63			80	100	0.05



Random sample generation to  
10 000 iterations



Table 15 – Developed spreadsheet for performing MCS for the Investment Cost performance criteria

	Limits Lower ; Upper 90 ; 100	Limits Lower ; Upper 60 ; 85	Limits Lower ; Upper 60 ; 75	Limits Lower ; Upper 35 ; 50	Limits Lower ; Upper 15 ; 25
Iteration No.	Investment costs 1	Investment costs 2	Investment costs 3	Investment costs 4	weighting
1	93	61	68	46	0.16
2	91	72	74	37	0.2
3	93	64	61	36	0.2
4	92	78	63	36	0.21
5	91	76	61	50	0.17
6	98	73	69	48	0.17
7	92	68	73	38	0.16
8	91	62	61	38	0.24
9	96	68	68	37	0.21
10	91	61	62	49	0.17
11	95	65	64	50	0.18
12	100	65	73	44	0.24
13	91	82	73	39	0.25
14	90	75	73	49	0.23
15	96	71	67	39	0.2
16	94	78	67	50	0.17
17	98	85	61	37	0.19
18	99	69	62	37	0.25
19	94	66	75	35	0.18
20	93	63	64	42	0.25
21	91	80	62	43	0.19
22	94	84	73	41	0.24
23	90	79	74	48	0.16
24	98	64	68	38	0.18
25	100	67	66	36	0.15
26	92	81	75	47	0.17
27	95	85	65	39	0.2
28	92	73	64	47	0.21
29	94	61	66	49	0.23
30	92	69	63	45	0.24
31	96	65	61	35	0.21
32	95	70	64	45	0.15
33	96	81	71	44	0.17
34	95	70	62	48	0.2
35	99	70	72	39	0.22
36	98	85	71	35	0.21
37	96	67	68	43	0.22
38	93	67	64	41	0.18
39	99	74	65	44	0.15
40	99	62	60	45	0.22
41	99	66	63	42	0.17
42	95	79	62	44	0.15
43	92	78	70	44	0.19
44	97	61	67	36	0.22
45	94	68	68	36	0.18
46	94	79	66	48	0.21
47	95	64	73	47	0.21
48	97	67	74	49	0.16
49	95	80	69	39	0.21
50	92	70	67	38	0.17
51	90	72	70	49	0.23
52	95	82	71	37	0.25
53	93	83	70	46	0.19
54	97	75	68	49	0.23
55	92	63	67	41	0.18

↓  
Random sample generation to  
10 000 iterations



Table 16 – Developed spreadsheet for performing MCS for the O&M performance criteria

	Limits Lower ; Upper	Limits Lower ; Upper	Limits Lower ; Upper	Limits Lower ; Upper	Limits Lower ; Upper
	87 ; 93	22 ; 28	22 ; 28	22 ; 28	15 ; 25
Iteration No.	O & M 1	O & M 2	O & M 3	O & M 4	weighting
1	93	22	26	24	0.17
2	88	28	27	22	0.16
3	89	27	23	27	0.23
4	90	28	25	22	0.23
5	88	24	28	23	0.2
6	91	24	22	25	0.25
7	89	26	28	25	0.2
8	87	24	23	22	0.15
9	87	26	23	26	0.23
10	90	28	28	22	0.23
11	89	26	24	28	0.22
12	91	26	26	26	0.21
13	92	23	22	22	0.17
14	88	26	23	24	0.15
15	90	28	27	23	0.24
16	89	23	26	26	0.23
17	91	22	26	25	0.2
18	93	22	28	27	0.18
19	87	24	28	27	0.21
20	89	23	28	26	0.23
21	93	26	24	23	0.21
22	89	28	28	25	0.17
23	89	22	27	24	0.23
24	90	24	22	24	0.17
25	92	27	28	26	0.18
26	88	28	27	26	0.2
27	92	25	23	28	0.16
28	92	27	28	26	0.23
29	92	23	27	25	0.23
30	91	23	24	28	0.25
31	88	27	22	28	0.16
32	87	23	24	27	0.23
33	90	22	25	27	0.21
34	87	26	23	26	0.19
35	90	24	27	25	0.17
36	87	26	28	25	0.2
37	87	23	24	25	0.21
38	89	28	26	22	0.24
39	92	28	24	25	0.18
40	87	24	27	23	0.2
41	92	27	24	27	0.21
42	87	24	22	26	0.19
43	91	22	24	24	0.17
44	90	24	26	24	0.2
45	93	26	25	22	0.18
46	90	22	26	24	0.15
47	88	23	25	22	0.19
48	87	24	28	27	0.2
49	88	28	26	22	0.22
50	93	24	27	23	0.18
51	90	22	22	22	0.23
52	90	22	27	27	0.18
53	90	26	28	28	0.19
54	93	26	23	27	0.23
55	88	22	26	26	0.22



Random sample generation to

10 000 iterations



Table 17 – Developed spreadsheet for performing MCS for the CO2 Cost performance criteria

Iteration No.	Limits Lower ; Upper 85 ; 100	Limits Lower ; Upper 85 ; 100	Limits Lower ; Upper 85 ; 100	Limits Lower ; Upper 30 ; 55	Limits Lower ; Upper 0 ; 10
	CO 1	CO 2	CO 3	CO 4	weighting
1	94	96	94	46	0.04
2	85	85	91	46	0.01
3	94	99	93	35	0.08
4	90	91	91	34	0.07
5	96	91	86	49	0
6	90	85	93	32	0.01
7	98	99	99	55	0.04
8	97	89	91	33	0.01
9	88	91	97	51	0.1
10	95	86	85	42	0.04
11	88	97	96	45	0.01
12	89	90	96	54	0.08
13	97	94	91	42	0.05
14	88	93	87	30	0.01
15	95	88	94	43	0.09
16	95	93	96	48	0.06
17	95	93	98	31	0.01
18	98	98	85	52	0.1
19	99	85	100	51	0.04
20	99	96	91	33	0.08
21	98	94	90	45	0
22	100	92	89	46	0.06
23	99	89	97	45	0.09
24	92	87	90	48	0.04
25	86	86	96	48	0.01
26	87	91	94	53	0.06
27	99	86	90	32	0.06
28	92	89	100	46	0.02
29	90	86	100	50	0
30	99	99	85	54	0.04
31	100	94	97	39	0.07
32	100	100	100	46	0.1
33	92	94	89	40	0.03
34	88	90	99	41	0.03
35	96	96	91	45	0.01
36	93	96	100	39	0
37	88	88	90	47	0.04
38	99	87	95	41	0.06
39	91	100	85	33	0.04
40	99	89	88	40	0.02
41	90	86	90	43	0.09
42	100	96	95	42	0.09
43	95	85	89	40	0.08
44	96	87	90	45	0.01
45	94	92	94	50	0.01
46	99	92	91	44	0.01
47	97	92	100	35	0.03
48	94	92	100	50	0.01
49	94	87	85	51	0.07
50	94	86	91	47	0.06
51	88	94	98	32	0.09
52	90	86	94	54	0.06
53	85	90	96	49	0.02
54	100	91	86	33	0
55	95	88	94	51	0.08



Random sample generation to  
10 000 iterations



