THE USE OF LIFE CYCLE COST ANALYSIS IN DETERMINING THE COST EFFECTIVENESS OF RAILWAY LINES' DESIGN AND MAINTENANCE OPTIONS FOR RAILWAY LINES THROUGH WINDBLOWN SANDY DESERT IN NAMIBIA

"CASE STUDY OF THE AUS – LÜDERITZ RAILWAY LINE"

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BY

JONAS HAMALWA

200727559

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Main Supervisor: Dr. Petrina Johannes

Co-supervisor: Prof. Dr.-Ing. Gerhard Bernstein

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KEY WORDS

Life Cycle Cost Analysis, Wind-blown Sand, Sand Mitigation Measures, Railway Infrastructures, Sand Ingress

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ABSTRACT

Railway transport in Namibia is one of the most important mode of transport with great importance to the economy of the country. Currently, road networks are the most important because of the low population density of the nation. However, railway lines have been reported to be the most economical, efficient, environmentally friendly, and the safe solution for long distance transportation of heavy goods [1]. The Namibian Railway Network lines linking to the coastal towns and ports, i.e. Swakopmund-Walvis Bay and Aus-Lüderitz Railway Line, are passing through the Namib Desert. Deposit of wind-blown sand onto the railway lines poses a great challenge to the maintenance and operations of this lines. The challenge for decision-makers is which solution is cost-effective to implement in the Namibia context to solve the problem. It has been reported widely [2, 3, 5, 7] that the best way to evaluate the cost effectiveness of different solution is by using the Life Cycle Cost Analysis (LCCA) approach.

The main objective of this study is to use LCCA, as an engineering economic tool, to determine the cost-effectiveness of the options to the challenging wind-blown sand on the railway lines passing through the desert. Specific objectives are: 1) Identify the best infrastructure design options and technical maintenance solutions for mitigating the sand problem onto the tracks. 2) Use the LCCA to evaluate the cost-effectiveness of the different solutions in order to recommend the best strategy. The study has exploded the knowledge of the LCCA of railway infrastructure in Namibia for both the analysts and decision-makers.

This study has presented a good insight of the LCCA as one of the best systematic approach to use to guarantee the best performance of the railway system. Ultimately the LCCA was successfully employed in the study to determine the cost-effectiveness of the solution(s) to combat the challenge of sand ingress onto the railway line. In the LCCA process, different alternatives were identified, discussed and analysed; which includes both railway infrastructure design solutions and technical mitigation measures. The LCCA results presented the Humped Slab Track to be the cost-effective solution compared to all other alternatives. However, it was further discussed that this option is only ideal for the sections where dynamic dunes are not crossing. This has proven that in as much as LCCA is a good engineering economic tool, it needs to be coupled with viability criterion/criteria in order to determine the cost-effectiveness of the design and maintenance solutions to combat the challenging problem of wind-blown sand on the railway line passing through desert areas. The study further proved that Tubular Track system was cost-effective compared to the Conventional Track system. The study provides a good insight of analysis to prove that Tubular Track system covered in the Tunnel System is the most viable and cost-effective solution to the sand problem along the dune belt. A number of recommendations for future improvement(s) and further researches were also proposed.

LIST OF ABBREVIATIONS

CWR	Continuously Welded Rails
EIA	Environmental Impact Assessment
EUAC	Equivalent Uniform Annual Cost
GRN	Government Republic of Namibia
IRR	Internal Rate of Return
K&A	Kleber & Associates
LCCA	Life Cycle Cost Analysis
MWT	Ministry of Works & Transport
N$	Namibian Dollar
NPV	Net Present Value
PA	Per Annum
PW	Present Worth
RSL	Remaining Service Life
STP	Social Time Preference
TNHL	TransNamib Holding Limited
M_c	Maintenance Cost
O_c	Operating Cost
°C	degrees centigrade
kg/m	kilogrammes per metre
km	kilometre
km^2	square kilometre
km/h	kilometre per hour
m	metre
m/s	metre per second
m^3	cubic metre

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CHAPTER ONE

INTRODUCTION TO THE THESIS

1.1. Introduction and Background

Railway transport in Namibia is one of the most important mode of transport with great importance to the economy of the country. Currently, road networks are the most important because of the low population density of the nation. However, railway lines have been reported to be the most economical, efficient, environmentally friendly, and the safe solution for long distance transportation of heavy goods [1]. Namibia has a good potential of mining and industrial activities, which made railways to be more ideal for transporting heavy goods for long distances because of their ability to accommodate heavy loads without damages to the permanent way or the facilities as compared to road transport. Due to the population growth, railway transport will be of interest to the country in future for both freight and passengers. It is therefore paramount to ensure its development and sustainability [1].

Namibia's Railway Network is currently operating on 2703 route-km length of track, which stretches from south to north, middle line to the east and the links to the coastal towns (Swakopmund, Walvis Bay and Lüderitz) [2]. Both Swakopmund-Walvis Bay and Aus-Lüderitz Railway Line pass through the Namib Desert, where at some sections the wind-blown sand is problematic to the railway operations. Large amounts of sand are deposited onto the rail track during the frequent sandstorms and efforts are done to keep the line clear of dune sand of varying sizes on the track.

1.2. Statement of the Problem

The Namibian Railway Network lines linking to the coastal towns and ports, i.e. Swakopmund-Walvis Bay and Aus-Lüderitz Railway Line, are passing through the Namib Desert. At some sections, the wind-blown sand poses a great challenge to the maintenance and operations of the railway lines. The harsh nature of the windblown sand clogs the tracks and may stop train operations for safety reasons. This infamous dune belt with its ever-shifting sand dunes has, since the beginning of operation of the coastal link lines, been an enormous burden to the Railway Authorities (TransNamib Holdings Limited (TNHL)) in maintaining the lines. The continuous invasion of the sand onto the track remained an unsolved problem until today in Namibia. This problem hinders the safe and reliable operations, reduces the availability, and increases the maintenance frequency of the railway lines.

There are different solutions for sand problems, which includes railway infrastructure design solutions and technical mitigation measures. However, the challenge for decision-makers is the identification of a cost-effective solution for implement in the Namibian context. Decision-makers are, therefore, expected to explain and justify decisions concerning the expenditure of the taxpayer's money on such infrastructure investments [3]. In [4], it is highlighted that decision making for railway infrastructure is a highly complex task that requires a trade-off between the required performance level (example safety and availability) and the lowest possible costs.

It has been reported widely [3, 4, 6, 12] that the best way to evaluate the cost effectiveness of different solution is by using the Life Cycle Cost Analysis (LCCA) approach. This approach is not commonly used in TNHL neither in the Ministry of Works & Transport (MWT), beside its many benefits. The LCCA is an important engineering economic tool to decision-makers as it helps in identifying the most cost-effective investment option thereby assisting them in making good decisions.

1.3. Objectives of the Study

The main objective of this study is to use LCCA as an engineering economic tool to determine the cost-effectiveness of the solutions to challenging wind-blown sand on the railway lines passing through the desert. To achieve this objective, the following specific objectives are set:

1) Identify the best infrastructure design options and technical maintenance solutions for mitigating the sand problem onto the tracks.
2) Use the LCCA to evaluate the cost-effectiveness of the different solutions in order to recommend the best strategy.

1.4. Significance/Justification of the Study

Due to high investment costs of the railway infrastructures, analysts (example engineers, transport economists, planners, etc.) and decision-makers (example government officers and politicians) are expected to clearly present analysis that support their decisions. Life Cycle Cost Analysis has been reported to be the best mechanism that enables decision-makers to identify the cost-effective railway infrastructure investment and allows for an implementation plan that guarantees the best service for the entire design life of the infrastructure [6]. The study will provide the knowledge of the cost-effectiveness of railway infrastructures passing through windblown sandy areas in Namibia. In addition to this, the study will save costs (maintenance, delay, renewal etc.), reduce delays, promotes safety, reliability, and the availability of the system.

The railway lines affected by the windblown sand deposited onto the tracks are all linking to the country’s main ports (Walvis Bay and Lüderitz Port). This further justifies the economic importance of this study, in the sense that the harbours, and a safe and reliable railway line system will stimulate the socio-economic growth of the country in general, the local citizens of the coastal towns in particular, the mining and fishing industry as well as the agricultural sector. In other words, Walvis Bay and Lüderitz are and will be the main routes for imports and exports, thereby stimulating the economic growth of Namibia at large.

A considerable number of jobs will be created directly or indirectly through a properly planned economic implementation strategy. Since bulk goods can only be economically transported inland by rail, effective rail transport will reduce the heavy loads on the roads, thereby reducing the high incidence of road accidents in the country. Having said all these, it is safe to accentuate that this study is of paramount importance because it is anticipated to contribute to the knowledge of railway transport infrastructure designs and investment decisions and stimulates the country’s socio-economic growth.

1.5. Scope, Delimitations and Limitations of the Study

This study was mainly focused on the LCCA of the railway infrastructure passing through windblown sandy Namib Desert on the Aus-Lüderitz Railway line in Namibia. The study area was considered because this line is important to Namibia in terms of the socio-economic development of the country. The study was confined on a 4.4 km section between km 294,100 to 298,500, chainage mark from Seeheim Station (km 0) to Lüderitz, along the Aus-Lüderitz Railway Line, refer to Figure 1.1. This is the only section along this route where sand deposition varies in volume and sizes, which helps in mapping all the potential solutions to the same area for comparison purposes. The procedures followed, results and findings of the study are expected to be useful to other railway sections in Namibia or elsewhere.

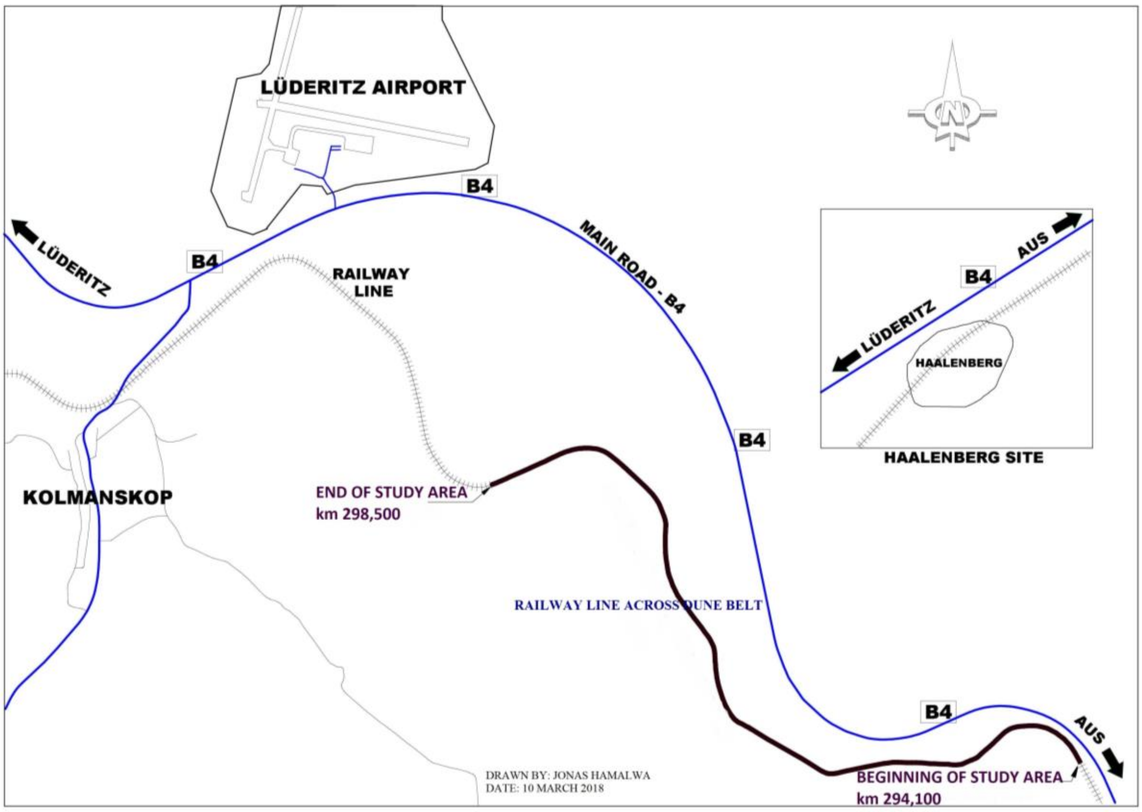

Figure 1.1: Locality Plan of the Study Area

The main limitation of this study is that the research work has only focused on the LCCA of infrastructure design and maintenance options for railway infrastructure passing through windblown sandy desert in Namibia, in the effort to mitigate sand problems on the railway line. Secondly, no test sections were constructed in this study mainly due to time and financial limitations. The LCCA approach will be employed to quantitatively determine if it can aid the investment decision making process. The research will compare different railway infrastructure design solutions and technical mitigation measures to sand problems. The other weakness faced was to get access or sufficient information required from responsible companies or bodies. Most of the companies are not willing to help academic researchers. It was difficult and took time to acquire information within a tight timeframe given.

1.6. Research Ethics

To guarantee a high ethical standard, the researcher has ensured that the policies and procedures designed to safeguard the research were adhered to. Basic ethical principles were strictly followed to ensure that the laws, policies, and regulations concerning the responsible conducts of the research at the institutional, governmental, and national level were observed.

1.7. Structure of the Thesis

The structure of this project report reflects the specific tasks undertaken as part of the study. Including this introductory chapter, this thesis is divided into five (5) chapters. The organisation and a summary of the contents of the other four (4) chapters are as follows:

Chapter Two (Literature Review): Presents a review of the core literature on aspects relevant to the study of the LCCA on sand mitigation measures for railway lines passing through wind-blown sandy desert.

Chapter Three (Methodology/Data Collection): Describes, in clear detail, how the study was undertaken. This includes how the different railway sections were studied to determine appropriate mitigation measures to the sand problem, how the cost analysis was undertaken, and how other relevant data were obtained.

Chapter Four (Results and Discussion): The chapter reports on the findings from the study, which entails the LCCA and evaluation of different solutions to the sand problem. The results were also interpreted and discussed in this chapter. The selection of the most appropriate alternative was also presented in this chapter. This chapter ties together the information explored in the literature review, the findings of the study and the conclusions and recommendations.

Chapter Five (Conclusions and Recommendations): Concludes the thesis by discussing the findings of the study as well as identifying limitations of the research undertaken. It furthermore presents the implications of research findings for further research on this area and provides recommendations to the government, TransNamib Holding Ltd. (TNHL) and industry stakeholders.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

This chapter consolidates the research evidence available and identify gaps in current knowledge concerning the long-term economic analysis of railway line's designs and maintenance strategies to mitigate the infamous deposit of sand into the railway line. In addition to this, the chapter lays a foundation for subsequent information presented in other chapters of this thesis.

2.2. TransNamib Holdings Limited as the Rail Operator in Namibia

TransNamib Holdings Limited, the rail operator in Namibia, was established in terms of the National Services Holding Company Act (Act no. 28 of 1998). It is stated in this act that the railways are transferred to the state and TNHL is solely responsible for the costs incidental to the maintenance of the railway including reinvestment required to maintain and operate the tracks. It is also agreed in the same act that the state shall fund the railway upgrading projects and TNHL shall inform the state in writing should they finance, design, construct any infrastructure for the railway [11].

2.3. Namibia's Railway Network

The railway network in Namibia currently consists of 2703 km main routes of tracks of 1067 mm gauges [2]. The railway network in Namibia is presented in both Figure 2.1 and Table 2.1, the study area is also marked on both.

Figure 2.1: Current Namibia Railway System [8]

Table 2.1: Lengths of Segments of Present Railway in Namibia [7]

RAILWAY LINES	ROUTE (km)
Nakop - Karasburg - Grünau - Seeheim - Keetmanshoop - Mariental - Rehoboth - Windhoek	865
Windhoek - Okahandja - Karibib - Kranzberg	210
Kranzberg - Usakos - Swakopmund - Walvis Bay	201
Kranzberg - Omaruru - Kalkfeld - Otjiwarongo - Otavi	328
Otavi - Tsumeb	64
Tsumeb – Ondangwa	246
Ondangwa – Oshikango	83

Otavi - Grootfontein	91
Otjiwarongo - Outjo	69
Windhoek (Gammams) - International Airport - Omitara - Witvley - Gobabis	228
Seeheim - Goageb - Aus – Lüderitz (Study Area)	**318**

2.4. The Aus-Lüderitz Railway Line (Study Area)

2.4.1. History of Aus-Lüderitz Railway Line

Aus to Lüderitz railway line was built during the colonial era in 1906 [7]. The design of the line was approved in May 1905 in Berlin [9]. It is further noted in [9] that the erection of corrugated sheet tunnels, not longer than 100 metres each, was recommended at five different places along the dune belt section of the route to mitigate the settlement of shifting sand on the tracks. The construction of this line was part of the war effort in the southern part of the country to serve as a supply line for military equipment and troops. The Germany military troops were responsible for assisting in the laying of the tracks using concentration camp labour from Shark Island. The history is frightening because 1359 of 2014 concentration camp prisoners used for this railway construction died while working on the line [7]. With this 67.5% mortality rate, it means that for every 100 m of this railway construction accounts for one dead Namibian Shark Island prisoner. The construction commenced at Lüderitz in March 1906 and Aus was reached in October 1906; it was then officially opened on 01 November 1906 [9].

In the time after, the line was used to carry passengers and freight to supply the southern part of Namibia with goods and for the import and export of general merchandise through Lüderitz harbour. The Railway Administration, however, found it difficult to maintain the line through all the years, particularly to keep the line clear of the dune sand especially on the section crossing the dune belt near Lüderitz [10, 22]. Up until 1990, four trains (two in and two out) per week were operating on the railway line, between Aus and Lüderitz [10].

By 1996 there was only one train into Lüderitz and one out per week. This single weekly train, carrying passengers and cargo, was not viable anymore and the line was closed in the mid 1996 due to poor track standards caused by lack of maintenance during the period between 1990 and 1996 and since 1997 the line was de-commissioned [10]. It is also argued in [10] that the biggest problems were mainly the aged tracks and worn sleepers and the recurring costs of removing the dune sand blown across the track by the frequent strong winds. The section of the railway line specifically affected by the windblown sand is between km 269,820 to km 302,800 (chainage mark from Seeheim Station (km 0) to Lüderitz).

2.4.2. Upgrading of the Aus-Lüderitz Railway Line

The rehabilitation project of this line started in 2000 while the actual construction started in August 2001 supervised by K&A Consulting Engineers, under the Ministry of Works and Transport (MWT) and the rehabilitation of was completed end of 2017. The total length of the rehabilitated line is 139.5 kilometres. It starts at an altitude of 1350 m at Aus, and after a steep descent, drops to 900 m over the first 25 km, it gradually descends over the rest of the line to sea level at Lüderitz. The line runs for its entire length through the Namib Desert. The area adjacent to the railway line consists mainly of sandy or gravelly plains, sand dunes, sand sheets and ephemeral plains and watercourses. Towards the coast the landscape changes to rocky outcrops interspersed with sand dunes. A dune belt starts at the junction with the road to Elizabeth Bay and ends at Kolmanskuppe, some 10 kilometres along the track centre line.

Initially, light duty steel sleepers and 20 kg/m rails were used in the construction of this line to accommodate 11.5 tons axle load [9, 10]. Along this line, certain sections were upgraded with 30 kg/m rails on light duty steel sleepers. Several sections especially after Aus station and approaching Lüderitz were constructed with steep gradients and sharp radius curves [7].

To upgrade the track-work from the existing 11.5 tons axle load to accommodate 18.5 tons axle load, the following improvements were executed [7, 29]:

- The replacement of 20 and 30 kg/m rails with at least 40 kg/m and 48 kg/m rails and the light duty steel sleepers with heavy duty steel and P2 concrete sleepers.
- The improvement of embankments to avoid sharp radius bends and steep grades, where possible.
- The construction of the new formation layers in accordance with the standards adopted by TNHL. The formation layer construction was completed in 2004 by RCC and Salz Gossow Civil Engineering Contractor.
- Provision of adequate hydraulic/drainage and other structures to protect the line, except between Aus Station and km 190,000 where the original embarkments were to remain.

The upgrade was done into two (2) phases, where:

<u>Phase 1 [7, 10, 22, 29]:</u>

- Section 1, Aus Station km 179,780 to km 203,800, is a Tubular Track System section with 30 kg/m rails. The 30 kg/m rails were reused for this section on the modular concrete beam system to enable 18.5 tons. These axle loads using 30 kg/m rails on a conventional track are not possible. Tubular Track System is a ballast-less railway system with rails continuously supported on reinforced concrete beams [24]. More details of this system will be discussed in subsequent sections.

- Section 2, km 203,800 to km 251,100, is a Conventional Track section with 40 kg/m refurbished rails on P2 concrete sleepers at 700 mm c/c nominal spacing and e-clip fasteners.

<u>Phase 2 [7, 10, 22, 29]:</u>

- Section 1, km 251,100 to km 269,800, is a Conventional Track section with 48 kg/m rails on P2 concrete sleepers at 700 mm c/c nominal spacing and e-clip fasteners, and 1200 m^3/km ballast (53 mm nominal).
- Section 2, km 269,800 to km 317,160, is a Tubular Track section with 48 kg/m rails.
- Section 3, km 317,160 through the entire length of the rail network in the Port of Lüderitz, is a Conventional Track section with 48 kg/m rails on wooden sleepers at 700 mm c/c nominal spacing and E3131 cast iron chairs & fastenings.

2.5. Climate and Wind Conditions

Generally, the project area is falling within the southern sector of the Namib Desert, the climate is dominated by its proximity to the strong winds of the South Atlantic anticyclonic system and the associated cold upwelling waters of the Benguela. To be more specific to the Lüderitz climate, it is classified as very arid (desert). Approximately 127 fog-days are recorded at Lüderitz each year; the Town receives around seven to eight hours of sunshine per day [34]. Precipitation increases from the west to the east of the //Karas Region and ranges between less than 50 millimetres (mm) (at Lüderitz) and 100 to 150 mm (at Keetmanshoop) per annum. Average annual temperatures range between less than 16 degrees centigrade (°C) (at the coast) and 20 to 22 °C (at Keetmanshoop) [34]. Maximum and minimum temperatures at Lüderitz during the hottest and coldest months range between 20 to 22 °C and 10 to 12 °C, respectively. Relative humidity in the Lüderitz area ranges between more than 90% during the most humid months and between 60 and 70% during the least humid months. The average annual rates of evaporation in the Lüderitz area range between 1,680 and 1,820 mm. Winds from the south predominate at Lüderitz [34].

During the summer months, sand storms occur frequently; average wind speeds of over 40 kilometres per hour (km/h) can be experienced at Lüderitz during summer afternoons [10, 34]. During the winter, high-pressure systems over the interior of southern Africa can cause occasional strong south to north-easterly winds. These “berg winds” can blow for a number of days and are characterised by very high temperatures and dry, dusty conditions. The section of rail where it is proposed to construct the Sand Shelter Tunnel lies in a dune belt. Throughout the year, and due to the strong winds blowing predominantly from the south, the dune sand constantly moves. Sand dunes in the area can reach heights of up to 30 m and move in a northerly direction for up to 60 m per annum [10].

2.6. Sand/Sediment Movement on the Dune Belt

The Sperrgebiet is a geomorphological dynamic area under the influence of an extremely arid climate and experiencing some of the strongest, unidirectional coastal winds of the African continent. These dynamics are analogous to movement on a gigantic, several thousand-kilometre-long sediment conveyor belt. Fine grained longshore sediment, trapped in coastal embayment north of the Orange River mouth are driven by the southerly winds, funnelled through topographic depressions, are forming barchan dunes, horn-shape crescents up to 30 m high that race northwards some 50-300 m per year under the lash of the aggressive southerlies [22].

The dune belt crossing this railway line (between km 269,820 to km 302,800) originates at Elizabeth Bay and first runs in a north easterly direction up to the B2 road from where it turns to the north west to join the wide sand desert area between Lüderitz and Swakopmund [9]. The major part of the shifting sand dunes is located east of a depression situated between Elizabeth Bay, the Lüderitz Airport area and the Agate Beach north of Lüderitz. This depression is free of shifting sand dunes and the prevailing strong winds have transported diamonds from the sea at Elizabeth Bay up to the area around Kolmanskop. The east depressing, locally called the Airport Corridor, the terrain rises some 100 metres (m) and more above the depression close to Kolmanskop. A barrier is formed, thus distorting the wind flow, resulting in the deposition of sand and subsequent formation of sand dunes. These dunes show extreme dynamic movements. The underlaying ground is of rocky nature with outcrops of various sizes, and in addition local rock projections in the area surrounding the road cause sufficient disturbance in the flow of the wind to cause the sand to be deposited onto the road [9, 10].

2.7. Sand Problems on the Tracks

The movement of sand dunes was and is an ever-present headache for the Namibian Railway Administration (MWT and TNHL). This is reported in [9, 10] that the infamous dune belt of the Namib Desert with its ever-shifting sand posed tremendous problems to the Railway Authority and remain unsolved. Large amounts of sand are deposited onto the rail track during the frequent sandstorms. This does not only pose operational problems but financial burdens as well during maintenance to ensure that the line is clear of dune sand.

It is a general understanding in the railway sector that sand and railways do not mix. The movement of sand dunes in desert railways therefore poses various effects on tracks [23]. The major consequences of sand on tracks includes increased maintenance and rehabilitation costs, reduced traffic speeds, relevant delays in train's operations and huge safety concerns. Specific challenges entail track blockages, ballast ingress/contamination, fouling of electrical systems, jamming of switches/gear boxes of the railway line. These railway problems in such areas should therefore be identified and efficient remedial measures accordingly introduced [23, 25].

According to [22] sand is recognised in various configurations as follows:

- Dunes can form up to 100 m high (and higher) mountains, which are stationary. Stationary dunes are much easier to control and under such conditions infrastructure can be laid out respectively.
- Walking dunes are more difficult to cater with. Sometimes temporary realignments are done, even temporary tunnels to let the dune walk over have been tried.
- Windblown sand is the most adverse enemy for railroading [22]:
    - The grain size of sand is very small, and it penetrates wherever a path to do so will be found. Especially locomotive drives, wagon axle boxes and other mechanical parts with relative movements are concerned. Infrastructure wise the locks and drive machines of turnouts suffer the most.

    - To a very severe extent also the interface rail/wheel gets out-of-face abrasion, leading to a much faster deterioration of wheel profiles than experienced elsewhere, resulting in the loss of running stability and consequently causing an accelerated loss of track geometry.

    - The most dangerous effect but is the non-predictable building-up of sand heaps over the track, which not only hide the track, but manifest an actual danger of derailing. Sand is not compressible and would not change its aggregate condition under high pressure. It will be compressed, and it will resist, and it will force the wheel to lift. A lift of 25 mm is more than adequate for derailment [22].

2.8. Studies on Sand Problem Worldwide

The problem of windblown sand is the main specific technical issue in design and construction of railway line traversing desert and arid areas. The detrimental effects of windblown sand effects on railways were recognized ever since the late nineteenth century. The sand problems are nowadays the environmental limiting factor that is inherent in reliability, availability, safety and serviceability of the existing railway line and future projects. A growing research and technical activity have addressed this problem in the last decade, in different fields across fundamental, environmental and engineering sciences [35, 36].

All over the world, different countries including Saudi Arabia, China, Iraq, Iran, Egypt, Libya, Algeria, Morocco, Australia, South Africa etc. face similar wind-blown sand problems on the railway line in desert areas. Different countries use different sand mitigating measures depending on the nature and condition of the sand problem and availability of resources. Different studies are carried out in these countries to mitigate the problem and ‘‘various pieces of experience have been gained and many research activities have been developed which have recognised dominant conditions, motional behaviour of dunes, and also remedial solutions in these countries’’ [23]. Windblown sand is the main specific technical issue in design and construction of infrastructures across desert and arid regions. Windblown sand harmful effects on railways were recognized ever since the late nineteenth century and are nowadays the environmental limiting factor that is inherent in safety and serviceability of actual railways and future projects [35].

According to a recent study [36] on the review of challenges and mitigation measures for windblown sand along the railway infrastructure, the following the first historical railways along deserts (see Figure 2.2) have been built by colonial countries [36]:

- The British military railway was built at the end of the 19th century (1897–1899) from Wadi Halfa to Abu Hamed over the Nubian desert.
- The French railway form Mecheria to Ain Sefra in Algeria was opened in 1887 across the norther part of the Kenadsa desert, and then extended to Beni Ounif in 1903, and to Colomb-Bechar in 1906, in the framework of the never finished Trans-Saharan Railway project.
- The German railway line from Aus to Lüderitz built in 1906 over the Namib desert [7]; and
- The Hejaz Railway was built from Damascus to Medina, through the arid Hejaz region of Saudi Arabia and was a part of the Ottoman railway network built from 1900 to 1908 with German advice and support.

Currently, most of the abovementioned first lines are partially or totally decommissioned, and their remains buried by accumulated windblown sand or encroaching dunes [36].

It is reported in [36] that first sand mitigation measures to combat sand problems on the railway lines have been empirically tested on the Sher Shah-Attock line in the arid Punjab province of Pakistan. It was further argued in [36] that the modern design of the Dammam-Riyadh railway line in Saudi Arabia, specifically the Kundian-Mianwali section, has systematically addressed the problems of windblown sand on the railways by applying the technology known from the snow mitigation measures. On the other note the 40 km Batou-Lanzhou railway built in 1956 was buried by the dynamic due from the start of the project. An initiative of developing an artificial ecosystem on mobile dunes was started by application of straw checkerboards over the mobile sand source and this system was widely used in China to combat sand onto the railway line [36]. Figure 2.2 shows a map of all these historical railway lines affected by windblown sand worldwide.

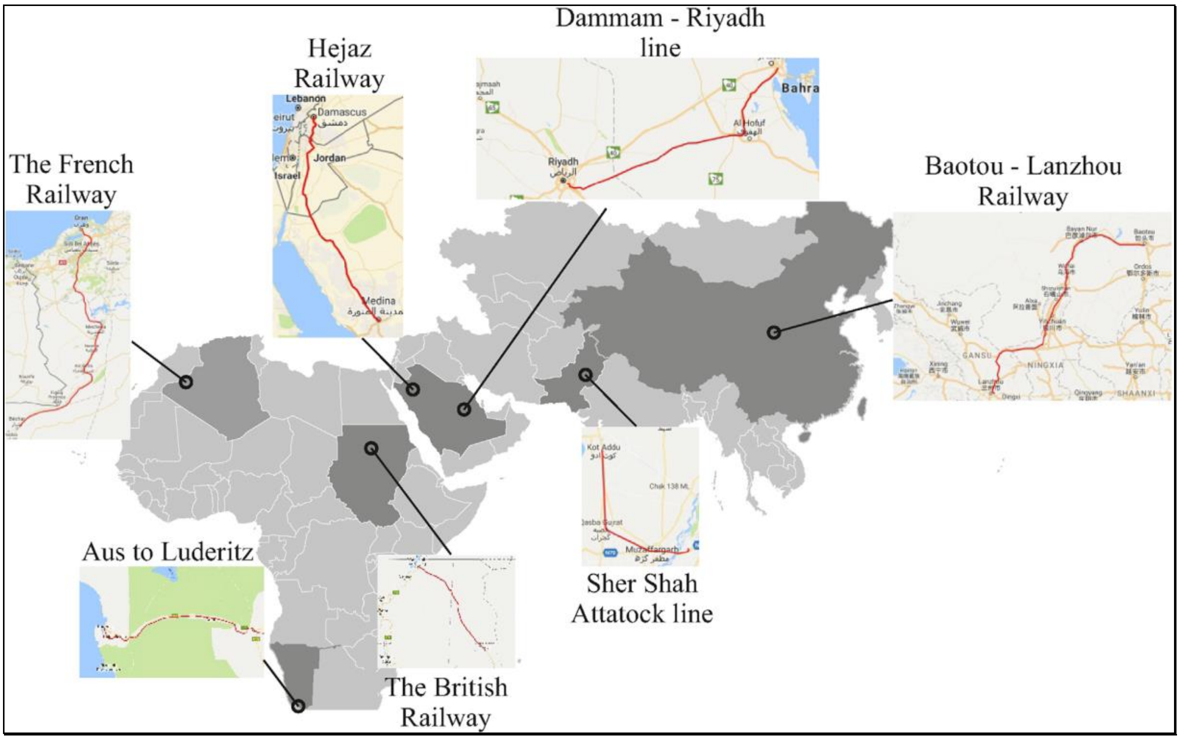

Figure 2.2: Historical Railway Lines in the Desert [36]

Effective, durable, robust and sustainable sand mitigation measures are required to achieve the highest performance range of the railway line. Wind-blown sand solutions differ in several ways, which includes:

- the planning and design;
- initial investment, operation, and maintenance costs, and
- the effectiveness of each solution depending on sand volumes and operational requirements and procedures.

Mitigation or Technical Measures to sand problems, used worldwide specifically in countries mentioned above including Namibia, include and not limited to:

- Sand Removal by hands (labour intensive)

- Sand Removal by Mechanical means (e.g. bull-dozer, on-track tractor, bob-cat etc.)
- Covering sand with hessian, wire mesh, chemical sand dune stabilisation (chemical agents)
- Stabilisation by erecting fences, barriers, vegetation etc.
- Specialised sleepers combat sand - System of elevating the rail seats
- Humped Slab Track
- Ballast-less Track System (Tubular Track System)
- Tunnel System

2.9. Studies on Sand Problem in Namibia

Several studies were undertaken in the past on behalf of the Department of Transport of the South West African Administration and the MWT of the Government Republic of Namibia (GRN), dealing with problems caused by wind-blown sand for the purpose of the railway line and the highway through sand dune desert areas as well as the aerodynamic investigations of this strong wind transporting desert sand. These reports were reviewed and those related to this study were selected and applied aspects to find the solution to the problem were analysed. A short summary of the studies reviewed is given in the subsequent sections:

a) CSIR Report MEG 454 (June 1966) – Aerodynamics Investigations into the wind transport of desert sand over a hard-top road [26]. This report was conducted in 1966, by the National Mechanical Engineering Research Institute Council for Scientific and Industrial Research, on request of the South West Africa Administration to assist proposing new road linking Walvis Bay and Swakopmund with a turn-off near Walvis Bay to Rooikop. The main objective of the investigation was to determine how susceptible a road through desert dune terrain would be to sand encroachment, and to study means of improving the sand deposition characteristics of the road. Three basic configurations studied were the road elevation (fills), road cuts through particularly high dunes and transitions from a fill to cut. In addition, the sand deposition characteristics of a road bridge crossing was also investigated. The report dealt with aerodynamic tests carried out to aid the study of sand encroachment problem on a road planned to traverse desert dune terrain. The static pressure and wind velocity traverses were made around solid road fill models of road fills and cuts and a road bridge crossing [26]. The conclusions of this study worth noting are demonstrated in Figure 2.3.

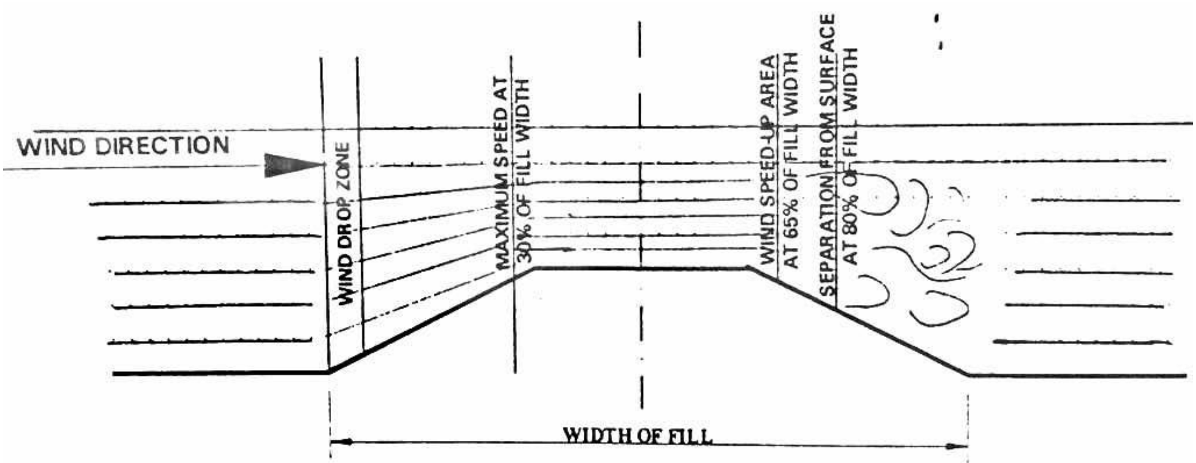

Figure 2.3: Typical Wind Distribution over Fill [26]

As shown in Figure 2.2 above, it was revealed that there is a decrease in wind speed upwind of the start of a fill and along the first section of a fill (some 500-1000 mm). After this the flow accelerates rapidly to a maximum wind speed at about 30% of the fill width. The wind speed then decreases slightly over the top with a tendency to speed up again at 65% of the fill width. At the downwind side of the fill the flow separates from the surface at about 80% of the fill width [26].

It was further discovered that as far as sand transport is concerned, it is predicted that the region of low speed upwind of fill will cause sand deposition there. The increased speeds from the foot of the fill to the windward edge could result in erosion of the fill surface. The speeds over the road should be sufficient to ensure transport of sand over it. The separation zone in the lee of the fill indicates a very likely region of sand deposition [26].

b) Investigation into construction of highways through sand dunes in vicinity Swakopmund – Walvis Bay by Kantey & Templer (1966) [27]. This study was requested by the Chief Roads Engineer of South West Africa Administration with the main aim to prevent the deposition of sand on the proposed road between Swakopmund and Walvis Bay. This investigation was carried out parallel to the CSIR study reviewed above. The study has strongly recommended the proposal of fill profiles as recommended by CSIR study. However, it is reported in [27] that the theoretically fill of minimum 10 meters high with 40 meters obstacle free horizontal area, on both sides of the road is not feasible. Therefore, Kantey and Templer in [27] have recommended an ideal embankment fill of 7.0 meters from the edge of the shoulder and have a slope of 1:4 followed by a 1:15 slope to a 1:2 slope would be of additional advantage.

c) Report on problems caused by windblown sand on trunk road 4/2 between Haalenberg and Lüderitz (1975) [28]. This report was compiled 12 months after the completion of the Trunk Road 4/2. The purpose of the report was to describe the factors affecting the deposition of wind-blown sand on the bitumen surfaced road between Haalenberg and Lüderitz. Haalenberg is between Aus and Lüderitz and the road IS constructed parallel to the railway line on the northern side of the railway line. The report was compiled based on the observations of the sand under varying conditions which occurred that year.

It is reported that all fills through the sand dune area have been constructed with parabolic side slopes, which were developed by CSIR [26], to accelerate the wind over the road surface and make the road self-cleansing. It was realized that self-cleansing action could only be effective as long as the road surface was higher than the tops of the approaching sand dunes. Clearly, if an approaching dune should be higher, then the road must fall within the wind ‘’shadow’’ of the dune which then move in its normal way onto and across the road surface. In avoiding this, wherever possible the road was constructed above the expected heights of the approaching dunes [28].

It was proven on this road that the parabolic cross-section is effective under ideal weather conditions, however from time to time conditions prevail which are not ideal. This was seen from serious sand problems developed with insignificant height approaching the road. It was also reported that wind velocity also plays an important part in determining whether sand will accumulate on the road. It was observed that very strong winds (>35 km/h), slight irregularities in cross-section or shoulder shape had less effect and the cleansing power of the wind by virtue of its velocity, was sufficient to prevent sand accumulating on the road [26, 28].

In light winds the problem was minimal due to the small quantity of sand transported and the short duration of such winds. Thus, it was observed that medium strength winds (15-25 knots) create the most problems, having sufficient power to transport sand but not sufficient to overcome the small aerodynamic disturbances caused by slight irregularities of the ground surface [28]. Under these medium conditions it has frequently been noticed that the deposition of sand is extremely sensitive to the shape and the smoothness of the shoulders and side slopes.

The worse sand problems experienced on the road during the period of the observation have been caused by frequent reversals of wind direction, with the force remaining in a critical range between 15-25 knots [28]. The report was generally concluded that under normal prevailing wind conditions on this area, the road is predominantly self-cleansing. When abnormal fluctuations in wind directions and velocities occur, sand will accumulate on the road at different unusual places [28].

Final report on the investigation of sand dune encroachment on trunk road 4/2 at Lüderitz (2003) [29]. This was a report prepared by K&A Consulting Engineers for the Roads Authority of Namibia with the aim to improve traffic safety and reduce high maintenance costs of the road, caused by large amount of sand deposited during the frequent sand storms onto the road. The consultants were tasked to study the extent of sand dune encroachment problem on the specific sections of the road and the surroundings, including the adjacent railway line. The consultants have identified, investigated, and reported on different options with cost estimates, pros and cons. Necessary guiding principles, advise on methodologies on how to implement the preferred option(s) were also documented.

Different sand control methods proposed and investigated in this study were stabilization (by gravel, chemical stabilizers and seawater), destruction method (removal of sand by mechanical equipment) and fencing or barriers of wooden poles and/or steel railway sleepers. The cost estimates for different options was also carried out in this report. It is reported that wind conditions around the Aus-Lüderitz route are much more severe than that in the area of Walvis-Swakopmund. The prevailing south-westerly winds are changing at times to strong north-eastly winds, and a reverse sand movement takes place. It was further noted that the movement of dunes in the Lüderitz area are much faster and the sand transportation is far greater compared to Walvis Bay [29].

d) Basic Planning Report – The construction of railway tunnels crossing the sand desert near Lüderitz (2007) [22]. The purpose of this report is to define the necessity for the erection of railway tunnels along the route, at the crossing of the dune belt some 24 km east of Lüderitz, the proposed locations and to firmly establish the general design features for constructions. The report also includes a technical and financial comparison of alternative construction elements and methods. The construction of the tunnels with pre-fabricated concrete sections was calculated to be the cheapest and most suitable method to provide adequate sand sheltering tunnel system between km 294,100 to 298,500 (chainage mark from Seeheim Station (km 0) to Lüderitz). [22].

In the past, on the Aus – Lüderitz Railway Line, large sand-clearing gangs carried out this time consuming and labour-intensive occupation as the relentless drift of shifting sand continues [14]. The removal of sand from the track by hand labour does not only cost the the Railway Authority but it also poses some inherent personnel safety issues to the labour force. Mechanical bulldozers are currently used for the removal of sand from the tracks. This mechanical operation has in places caused severe damage to the track components, thus creating an even greater burden on the track maintenance and operation. Continuous mechanical breakdowns of plant due to the harsh on-site weather conditions has also proved to be a burden especially in maintaining the plant in this harsh working condition. According to [10], all attempts to prevent the sand from invading the track, like covering the sand dunes with hessian, wire mesh and coarse gravel were only a short-term solution. Corrugated iron tunnels were built at some time which, however were not adequate and too weak to solve the problem [10]. This area is also subject to high corrosion due to the proximity of the sea.

The Consultants of Kleber & Associates have been for the past ten years observing and studying the behaviour of the dunes and their effects to the railway line and subsequently propose and design the most effective solution to the problem [10]. The tunnel is one of the solutions recommended to the sand problem on the sand belt. Other options explored were including removal of sand by manpower (manual labour) and mechanical means (on-track machines were also considered), mechanical and chemical sand dune stabilization were among the alternatives looked at. Stabilization was tested by erecting fences, barriers, as well as coverage with chemical stabilizing agents. The conclusion of all testing and field experiments was, that stabilization of the dunes can only stop the migration of the dunes for a short period and does not offer a permanent solution [10]. TransNamib Holdings Limited [2] has also presented a system of elevating the rail seats with the help of "humps" on the ballast imbedded ties that allows free flow of air and sand transportation across the track under the rails and keeps the contact area between the rail and wheel virtually free from highly abrasive sand, thus increasing the lifetime of the wheel profiles [25]. Figure 2.4 below shows how fencing and sand stabilisation were carried out on the Aus-Lüderitz Railway Line in the past. Figure 2.5 also shows the vegetations as an effective sand control method.

Figure 2.4: Fencing and Sand Stabilisation on the Aus-Lüderitz Railway Line [22]

Figure 2.5: Vegetation Cover as a Sand Control Method [22]

2.10. Life Cycle Cost Analysis

2.10.1. Definition

Life Cycle Cost Analysis can be defined as a method for calculating the total cost of a system or a product over its total life span [12]. In transport economics context, LCCA can be defined as an evaluation technique applicable for the consideration of certain transportation investment decisions [5]. It is further argued that the tool is used to compare the total cost of different project alternatives. In details, LCCA can be described as a technique for evaluating and quantifying the total economic value of the project alternatives by accounting and analysing the initial costs, discounting future costs (operating, maintenance, and rehabilitations costs) and the salvage value of the project, over its life span [6].

2.10.2. Life Cycle Cost Techniques

The LCCA states that the implementation plan with the lowest total costs over the entire life span of an infrastructure is desirable. The action taken during the design, construction, maintenance, and operation of the infrastructure has a cost and revenue implications at the end of the life span of the infrastructure [3]. Furthermore, to have effective cost comparisons of different alternative solutions, all costs should be discounted to the same time base line. Moreover, it is important to convert all costs to the same units when carrying out an economic analysis.

There are many methods that can be employed to carry out an economic evaluation of transportation projects. These include Present Worth (PW) also known as Total Present Value (TPV) or Net Present Value (NPV), Equivalent Uniform Annual Cost (EUAC), Benefit Cost Ratio (BCR), Internal Rate of Return (IRR), etc [3].

2.10.3. Life Cycle Cost Analysis Steps

In order to properly and thoroughly execute a good LCCA, procedural steps should be identified. The following steps are outlined in [5] and [6]:

Step 1: Establish Design Alternatives

Step 2: Determine Performance Periods and Activity Timing

Step 3: Estimate Costs

Step 4: Compute Life Cycle Costs

Step 5: Analyse the Results

The above steps are generally in a sequential order; however, they may be changed to fit for the requirements of a specific analysis.

According to literature [3, 4, 5, 6, 12] the LCCA technique is the best tool to evaluate the cost effectiveness of different competing solution in the designs and development of railways. Decisions taken during the design, construction, maintenance and operation of a railway line can have an impact on the costs and revenues during the residual economic life [5]. In order to make these costs and revenues comparable, i.e. to express them in equivalent currency units, the cash flows occurring during the analysed life span are discounted to a base year, in which the decision is being made [5, 6]. The LCCA is an important engineering economic tool to decision-makers as it helps in identifying the most cost-effective investment option thereby assisting them in making good decisions [4, 33].

The LCCA builds on the substantiated principles of economic analysis to evaluate the overall long-term economic efficiency between competing alternative design and maintenance options [12]. It is stressed in [35] that minimizing the track system life cycle costs increases the sustainability of the rail superstructure. The detailed analysis of the costs over the entire life cycle of each track solution allows assessing the trend of agency (e.g., construction, inspection, maintenance and renewal), user costs of the alternatives and recognizing the most convenient [36]. A life cycle costing assessment considering also Reliability, Availability, Maintainability & Safety (RAMS) analysis provides a way to optimise the maintenance strategy, considering the short-term budget requirements as well as long term costs of agency [12]. To achieve overall RAMS requirements and LCC objectives of the system, it is important to follow systematic LCC assessments throughout the life cycle of the system [12, 35].

2.11. Summary

This chapter has attempted to provide an extensive published literature concerning the wind-blown sand that poses a great challenge to the maintenance and operations of the railway lines passing through desert areas. However, there is limited published literature regarding the problem of sand deposits onto the railway line in the Namibian context. Nevertheless, the review has touched on different similar studies carried out elsewhere for similar problem worldwide and in the study area. It further attempted to give a greater understanding of the wind-blown sand behaviour and wind dynamics of the study area. Different mitigation or sand control measures that were used before, currently used and the ones not yet employed on the study area were reviewed. The review has finally explored on the LCCA approach as an engineering economic tool to determine the cost-effectiveness of different solutions to combat the challenging wind-blown sand on the railway line passing through the desert area. The next chapter will present the methodology employed to collect relevant data of this research project.

CHAPTER THREE

METHODOLOGY AND DATA COLLECTION

3.1. Introduction

This chapter describe how the research was undertaken. The main aim of the chapter is to explicitly report on how data was obtained, and the procedures used to determine the LCCA. The focus of this chapter is mostly on the research design of the study, data collection methods used to acquire input data, the methodology and procedures used to undertake the LCCA and how the results were analysed.

3.2. Research Design

This research used both qualitative and qualitative approaches. To achieve the objectives outlined in the previous section, the technical input data and information are gathered and an economic assessment is performed. Life Cycle Cost analysis is purely data-intensive, and this qualifies the use of a quantitative research design method. On the other hand, a qualitative research design method was also employed in this study when dealing with other sections of the study, such as the establishment of design alternatives to sand problem.

3.3. Data Collection Methods

In this study, both primary data and secondary data from the government offices, companies such as TNHL, economic and engineering consultants, institutions such as banks, and other relevant bodies were collected. Like with any other quantitative analysis techniques, the quality of the LCCA depends on the input data used. Both qualitative and quantitative data were collected through a comprehensive literature reviews and consultations with experts. Data collected includes the appropriate design options or maintenance technical solutions, including their specifications and costs. The costs include initial investment costs (design and construction costs), operational costs and maintenance costs until the end of the life span of the alternative solution.

Uncertainty associated with input data and their implications to the results of the analysis were recognised and discussed. The analysis required some input information that were not directly available from information system or data management system. As a result, most of input data were derived from multiple data sources. Historical data agency and senior experts provided wealth information that were helpful to this study.

3.4. Life Cycle Cost Procedures

In short, the procedural steps of the LCCA can be summarised following the descriptions as outlined in [5] and [6] as illustrated in Figure 3.1. These steps are further described in the subsequent sections.

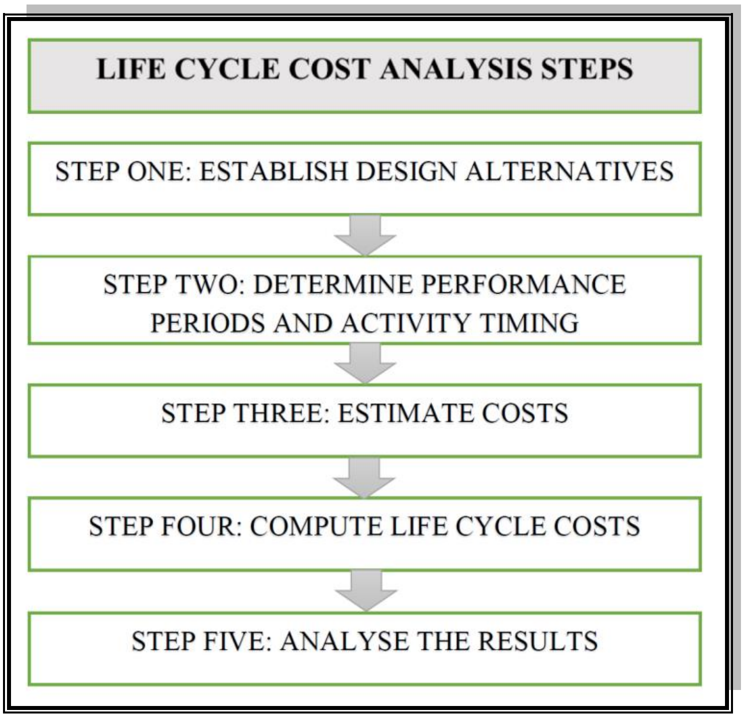

Figure 3.1: Life Cycle Cost Analysis Steps

3.4.1. Step 1: Establish Design Alternatives

The LCCA starts with the establishment of alternatives to accomplish the objectives of the project. Wind-blown sand mitigation measures differ in several ways, which includes the planning and design; initial investment, operation, and maintenance costs. The effectiveness of each solution depends on sand volumes and operational requirements and procedures to be followed to execute the alternative solution to the problem. To produce results that are comparable, the study was focused only on 4.4 km section between km 294,100 to 298,500, chainage mark from Seeheim Station (km 0) to Lüderitz, along the Aus-Lüderitz Railway Line. This is the only section along this route where sand deposition varies in volume and sizes, which helps in mapping all the potential solutions to the same area for comparison purposes.

Based on the previous studies carried out on the study area, some of the sand control measures applied worldwide are not applicable to the sand problem on this study area. Therefore, for the purpose of this study, only applicable solutions were used for the LCCA. Solutions such covering sand with hessian, wire mesh, chemical sand dune stabilisation (chemical agents) stabilisation by erecting fences, barriers, etc., were all used in the past on the study area but yielded no good results to mitigate the problem. Covering the dunes with vegetation was and will never be attempted due to the dry desert area the railway line traverses.

3.4.2. Step 2: Determine Performance Periods and Activity Timing

3.4.2.1. Service Life and Analysis Period of Design Alternatives

The alternative design solutions have different service life, which is the time frame the infrastructure is available for a normal good use to serve its purpose, the infrastructure has to continuously be serviced by carrying out regular inspection and maintenance. Performance life period prediction was determined based on the design life of the solutions and not forgetting the maintenance and rehabilitation of the systems under review [5, 6]. In this study, a common analysis period of 100 years was used throughout as a base period to assess cost differences between these competing alternatives so that the results of the LCCA can be fairly compared. The analysis period was determined from the design life of the design alternatives of which all are 100 years. Each alternative solution does not have the same maintenance or rehabilitation period, it is therefore important to note that more rehabilitations are carried out at some alternatives due to their deterioration or aging. In this study the analysis period was made long enough to ensure that at least one major rehabilitation activity for each alternative solution is covered. The assumption of a life time or service life of an alternative solution does not necessarily mean that the structure will no longer be fit for its purpose at the end of the analysis period (see Figure 3.2). This means that the service life continuous beyond the end of the analysis period depending on the condition of the infrastructure.

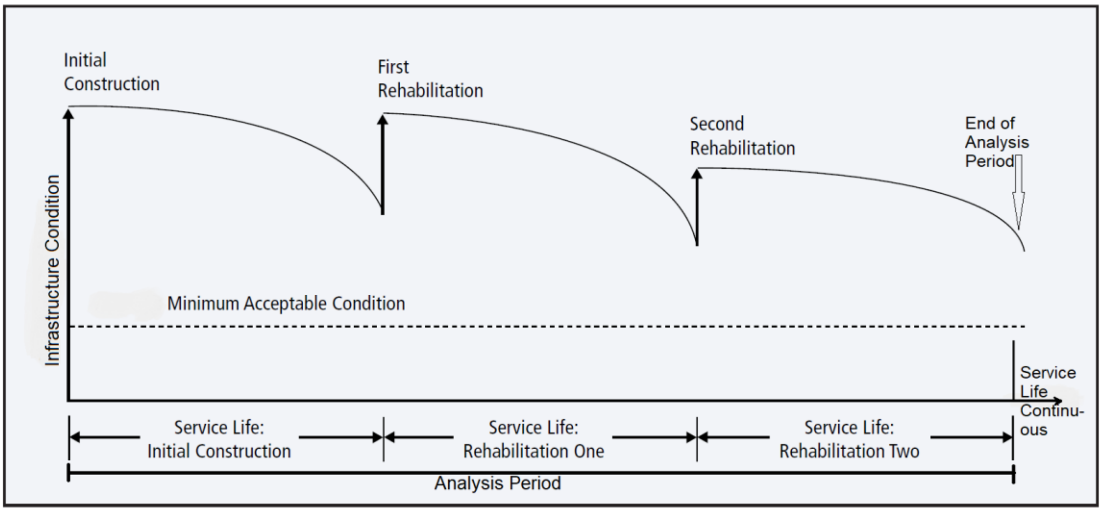

Figure 3.2: Analysis Period of a Design Alternative, Adopted from [5]

3.4.2.2. Activity Planning and Timing

For all alternative solutions developed, individual maintenance and rehabilitation strategic plan was developed after identifying maintenance and rehabilitation activities required for each alternative solution as shown in Table A1 under Appendix A. The maintenance and rehabilitation plan made it easier for the analyst to schedule when the future maintenance and rehabilitation activities should be carried out, for how much, when and for how long the operator (TNHL) can give the occupation time to the maintenance team or the contractor to do the rehabilitation. Each alternative solution has several rehabilitation and maintenance intervals expected due to the age and use of the infrastructure [31]. The prevailing weather condition on which the alternatives are exposed i.e. coastal weather and strong wind carrying desert sand, and other factors that may lead to the deterioration of the infrastructure is also important to consider. Deterioration of the infrastructure results in the down fall of the level of performance of the infrastructure. It is therefore, of paramount importance to carry out periodic maintenance and rehabilitation activities to improve and maintain the quality, performance and safety of each alternative solution.

Figure 3.2 illustrates the typical service life process in which each alternative solution is assumed to undergo starting from the initial construction stage, deterioration to the rehabilitation stage of the alternative. With this process it is easier to predict the service life of each alternative solution. The timings of the future rehabilitation and maintenance plan of each alternative solution is highly dependent on the rate of deterioration of the infrastructure. It is therefore important to note that the accuracy of the LCCA of each alternative solution depends on the validity of the anticipated maintenance and rehabilitation strategies planned.

The decisions related to the rehabilitation and maintenance of the track were taken in order to keep a balance between economic and safety aspects of the whole railway system. The main objective of the rehabilitation and maintenance plan is to develop operative procedures to optimise the track life span thereby increasing the track availability to the user. In other words, the plan helps in estimating costs of a maintenance/renewal works, assist in the choice of the best maintenance option/strategy in terms of economic return under specified time and financial constraints, and aid in timing of maintenance and rehabilitation/renewal activities in the most effective way. Different components of the railway asset are structurally and economically interdependent, however it is difficult to integrate their cost estimates, therefore, these costs are discussed and assessed together with the experts to include them in the decision-making. Degradation of the infrastructure, maintenance and renewal were considered at relevant timeframe planned as indicated in the maintenance and rehabilitation strategies and timings [33].

3.4.3. Step 3: Estimated Costs of Different Design Options

Costs considered in the analysis are all real costs incurred directly by the agencies over the whole life span of the alternative solution. The costs typically involved initial investment costs, operating costs, maintenance costs, rehabilitation costs and disposal costs. In this LCCA cost estimation exercise, only costs that demonstrate the differences between alternatives were considered. In other words, not all cost related with each alternative were calculated example the costs that are common to both alternatives such as costs for the acquisition of land, costs for Environmental Impact Assessment (EIA) studies etc. were not included in the cost estimates, because they are common to both solutions [33]. This is done in the effort to simplify the analytical and data requirement considerably. The estimated cost data for construction were based upon the current averaged tendered rates, operating and maintenance cost estimates were mostly obtained from TNHL officials, and other costs were drawn from historical records and engineering judgements by experts.

For all alternatives, salvage value and Remaining Service Life (RSL) value were considered in the cost estimation. The Salvage value is the remaining value of the investment at the end of the alternative's life span. Remaining Service Life value is referred to as the residual value of the alternative solution when its service life extends beyond the end of the analysis period. Each alternative solution has its own RSL value. Remaining Service Life value is totally different from the salvage value in the way that RSL value exists only if the alternative continuous to operate after the end of the analysis period, whereas the salvage value requires termination and only get some actual value after the sale or reuse of the scrap materials. [5, 6, 33].

3.4.4. Step 4: Compute Life Cycle Costs

By employing an economic technique known as discounting, these costs are discounted into present values and added up for each alternative. The analyst can then determine the most cost-effective alternative. However, after the analysis of the results it is important to note that the lowest option may not necessarily be the best for implementation after aspects such as risks, financial constraints, environmental issues and political concerns are taken into account.

The main aims of the LCCA is to evaluate the long-term efficiency between alternative investment options to mitigate sand problem on the railway line, analyse the impact of all other associated costs of each alternative in addition to initial investment costs, and finally to aid decision-making process on the choice between competing alternatives. To carry out an effective analysis of life cycle cost of the track infrastructure, it is essential to comprehend all the parameters that influence the LCCA and what is required for the analysis. As described in previous sections the LCCA approach identifies all the accrued future costs and benefits and reduces them to their present value by employing the discounting technique developed in previous sections through which the economic worth of alternative solutions to combat sand ingress onto the railway line is evaluated.

To achieve the primarily aims of the LCCA, the previous sections of this analysis looked at the descriptive development of the alternative solutions to mitigate the problem, the analysis period and timing of maintenance and rehabilitation, determination of the initial investment costs; operating, maintenance and rehabilitation costs, and the cost related with salvage and RSL value of each alternative solution. At this point, the objective of this LCCA step is to calculate the total life cycle costs for each alternative solution so that the solutions may be compared to aid the decision-makers in determining the most cost-effective solution.

After all costs and timings for different alternatives were developed, future costs of each alternative solution were discounted to the base year and added to the total initial investment cost to determine the Net Present Value (NPV) of each alternative solution. The understanding here is that the money spent at different times have different present values, the projected/future costs to be incurred for an alternative cannot simply be added together to compute the total LCCA of such alternative. The NPV, an economic indicator of choice in this study, was used to convert the expected future costs to present monetary values so that the life cycle costs of different alternative solutions to combat sand problems on the railway line may be directly compared.

3.4.5. Step 5: Analyse the Results

The last step of this LCCA process is the analysis and interpretation of the LCCA results. The steps of the whole LCCA process are arranged in an orderly way so that the analysis builds upon information gathered in the previous step(s). The LCCA is highly dependent on the assumptions and estimates made during the analysis or in the process of data collection. It is possible to improve the quality of the estimates and assumptions by using historical data or carrying out statistical analysis, however some uncertainty will still exist with the estimates and assumptions made [5, 6]. After computing the LCCA, it is imperative to address the variability and the uncertainties associated with LCCA input data such as activity cost, timing and discount rate. There are two methods that are being used to analyse the LCCA results, namely: the deterministic and probabilistic approach [5, 6].

The deterministic approach uses the discrete values assigned to individual parameters, whereas the probabilistic LCCA uses the value of individual analysis inputs to be defined by a frequency or probabilistic distribution. In this study, the deterministic approach was used because it is very simple to use and its does not require sophisticated software, but it can be conducted manually using a calculator or a Microsoft Excel spreadsheet, which was used in this study. In the deterministic analysis carried out in this study, a sensitivity analysis technique was employed to optimise the analysis. This approach includes changing a single input parameter such as the discounting rate or initial cost or other costs, over the range of its possible values while holding all inputs constant, and estimating a series of output LCCA values, where individual LCCA results shows the effect of the input change. In other words, sensitivity analysis is a technique used to determine the influence of major LCCA input assumptions, projections, and estimates on LCCA results. In a sensitivity analysis, major input values are varied. The input values are varied either within some percentage of the initial value or over a range of values while all other input values remain constant and the amount of change in results is recorded. The input variables may then be ranked according to their effect on results obtained. Like many other LCCA sensitivity analysis, this study laid its focus on evaluating the influence of the discount rate used on LCCA results.

3.5. Data analysis

In order to identify the best infrastructure design options and maintenance solutions or strategies for mitigating the sand problem onto the tracks, it is important to evaluate the effectiveness of the solutions. The LCCA was determined to evaluate the cost-effectiveness of the different solutions in order to recommend the best strategy. Among many other economic indicators as presented in the literature review, the Net Present Value (NPV) method was chosen and used in this study to determine the LCCA. The main reason for this choice was that alternative solutions to sand problem are transportation projects that can be implemented to serve for a long period of time. It is, therefore, important to consider the time dependent value of money over the life span of the project. In addition to this, there is a strong agreement in the literature on the effective used of the NPV as the most economic efficiency indicator of choice [6].

The general expression of NPV is given in equation 3.1. below [5].

$$NPV = \sum_{n=0}^{n} \left[\frac{1}{(1+i)^n} C_n \right] \qquad \text{..(3.1)}$$

Where: n = service life of the project in years

C_n= facility and user costs incurred in years (Future Value)

i = discounting rate

The component of $(1+i)^{-n}$ in the above equation is called Present Value (PV) factor for a single future value and time. The PV at a particular future amount is determined by multiplying the future amount by relevant PV factor for the particular future time (year) under review.

The selection of a suitable discount rate *i* is a very important to decision in the LCCA, because the discount rate significantly influences the results of the analysis. Discount rate affects the analysis results in a way that a high discount rate tends to favour options with low investment cost, short life span and high recurring cost, whereas a low discount rate tends to have the opposite effect [31]. The discount rate can reflect the effect of the real earning power of money invested over a period of time or it may also reflect the effects of inflation. Just as the case of costs, the LCCA can either use real or nominal discount rates. The type of costs used in this study are the real costs, therefore real discount rate was also used to compute the LCCA. Real discount rates reflect the true value of money with no inflation applied, it should therefore be used in combination with non-inflated future cost estimates; while in the nominal cost estimates inflation components are included and it should therefore use the inflated discount rate to compute the LCCA for the alternatives [4, 5].

The determination of the discount rate should be reasonable to reflect the historical trend over long period of time. The literature has shown that the historical trend over very long periods indicates that the real time value of money is approximately in the range of 3 to 4 percent [31]. Many literatures offer little in the way of selecting the appropriate discount rate. In the case of public projects such as this, which is funded by the government from taxpayer’s money, the discount rate has to be reasonable and consistent with the opportunity cost of the public at large. The discount rate *i* used in this study for all the alternatives evaluated was, therefore, as assumed to be 3% because of the Social Time Preference (STP). The theory behind STP is that the discount rate should not be too high because public projects are characterised by the advantages of the whole national economy and the interest of the whole public at large [32].

The determination of LCCA required a computer assisted calculation procedure, that could be done with the LCCA package but was not accessed, a simple Microsoft Excel was therefore used. One of the crucial issues is the reliability of data used for the estimation of costs, and assumptions made for the discount rate or interest rate, future maintenance and rehabilitation costs, etc. It is, therefore, important to analyse the robustness of the input data. Sensitivity analysis was conducted to identify the impact of the uncertainty of this study.

3.6. Summary

The essence of the LCCA approach is to obtain, record and use data on current activities but for the benefit of future asset acquisition decisions. In order to develop an effective and practical LCCA, sufficient and quality input data has to be collected. The decision making through this economic assessment is heavily dependent on validity of the input data used. This chapter has not only explored the methodology used in collecting input data but also the approach used to develop the LCCA. The next chapter will cover the presentation and the analysis of the results and findings of this study.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents, interpret and discuss the foremost results and findings of this research. The validity of information obtained during data collection dictates the quality of the LCCA. The LCCA is highly dependent on the assumptions and estimates made during the analysis or in the process of data collection. All data collected are presented in the following subsections. The chapter will further provide a vital link between data collected by tying together the information explored in the literature review, the findings of the study and the conclusions and recommendations. Furthermore, this chapter will assure that the main objective of this study, as to use LCCA as an engineering economic tool to determine the cost-effectiveness of the solutions to the challenging wind-blown sand on the railway lines passing through the desert, has been achieved.

4.2. Different Railway Design Options

The choice of the appropriate design solution and the maintenance strategies of the railway line are key-factors in the decision-making process for the identification of the most competitive and sustainable solution. Different railway design options and their technical maintenance solutions for mitigating the sand problem onto the tracks were identified as tabulated in Table 4.1. The details of these design options are further discussed in the subsequent section, where they are briefly described, and their advantages and disadvantages of each option are outline as a choice to mitigate the sand problem onto the railway line.

Table 4.1: Design Options and Maintenance Solutions to Mitigate Wind-blown Sand

Design Option	Maintenance Option
1. Conventional Track (Ballasted Track)	Sand removal by hands or manual labour.
2. Tubular Track (Ballast-less Track)	Sand removal by hands or manual labour.
3. Conventional Track (Ballasted Track)	Sand removal by machinery.
4. Tubular Track (Ballast-less Track)	Sand removal by machinery.
5. Humped Slab Track (Ballast-less)	Self-cleansing, minor sand removal by hands or machinery.
6. Humped Ballasted Track (Pedestal Concrete Sleepers)	Self-cleansing, minor sand removal by hands or machinery.
7. Conventional Track- Sand Shelter Tunnel System	Minor sand removal by either hands (manual labour) or machinery on the tunnel escape stations and portals (entrance / exit).
8. Tubular Track System - Sand Shelter Tunnel System	Minor sand removal by either hands (manual labour) or machinery on the tunnel escape stations and portals (entrance / exit).

4.2.1. Conventional Track - Sand Removal by Hands

One of the the maintenance options of this design option is the operation of removing or clearing sand from and around the track manually by manpower or labour using relevant tools such as spades (see Figure 4.1). This labour-intensive operation differs depending if the track is ballasted or ballast-less track. The ballasted track referred to in this study is the Conventional Track System constructed of 48 kg/m rails on P2 concrete sleepers at 700 mm c/c nominal spacing and e-clip fasteners, and 1200 m^3/km ballast (53 mm nominal) and layerworks as illustrated in Figure 4.2. The Conventional and the Tubular Track System referred to in this study are currently as installed at the Aus-Lüderitz Railway Line. Working in this area of heavily blown-sand is a health hazard to the people especially when the wind reaches 35 km/h and above people are unable to work in this harsh condition. The main disadvantage of this sand control method is that when the condition is not favourable for people to work, sand builds-up on the track making the line unavailable for use by the operator(s).

Figure 4.1: Sand Removal by Manual Labour [10]

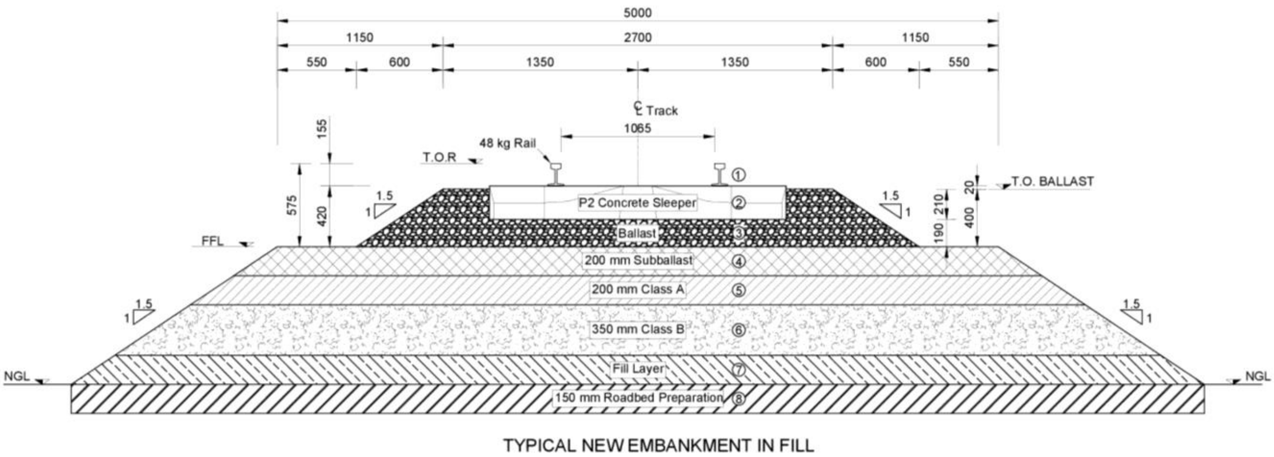

Figure 4.2: Conventional Track System Cross Section on the Aus-Lüderitz Railway Line

It is important to discuss the benefits and implications of each alternative generated because it helps in the decision-making process. Table 4.2 discusses the advantages and disadvantages of this design option.

Table 4.2: Advantages and Disadvantages of Conventional Track - Sand Removal by Hands

Advantages	Disadvantages
Design Option 1. Conventional Track - Sand Removal by Hands	
Construction method is simple, and the maintenance method of the track is easy to execute.	Maintenance and operating costs are very high and cumbersome to carry out with manpower.
Removal of sand can provide jobs to the local citizens.	Working in the harsh condition of strong wind-blown sand is a health hazard to the labourers.
Ballasted track has good drainage performance.	The availability, reliability and the safety of the line is not guaranteed. Night train movements may be restricted.
	Ballast fouling with sand reduces the structural ability in the performance of the track superstructure.
	This solution does not prevent the sand to be blown and deposited onto railway line. Dynamic sand dunes and some severe sand storms crossing the railway line may at times completely cover the line and will affect train operations.
	If there is any omission of ballast during placing, this will have a significant implication in terms of the construction costs and the longer-term maintenance costs.
	Loss of geometric stability is one of the main drawbacks of this solution. Ballast spreads and settles resulting in the loss of vertical and horizontal alignment.
	Loss of track resilience resulting from ballast degrading and becoming contaminated by sand. This results into increased dynamic damage to the track structure (corrugations) as well as to the rolling stock.

	Ballast requires regular tamping cycles and cleaning and/or replacement at a shorter rehabilitation period. Inevitably some damages are caused to other components of the track system during tamping, particularly the turnout sets.
	Pumping of sub-ballast layer-works caused by dynamic loading, results in ballast fouling from below, and destruction of formation, is another implication of this alternative.
	Ballasted track has higher noise level than non-ballasted track. It is necessary to take effective noise reduction measures.
	Ballasted track has a relatively low life span, as maintenance, rehabilitation, or renewal, has to be done in short intervals compared to a slab track.

4.2.2. Tubular Track System - Sand Removal by Hands

Although most of the current railway tracks are still of a traditional ballasted type, recent applications tend more and more towards ballast-less track. The major benefits of slab track are low maintenance, high availability, low structure height, and low weight. In addition, recent life cycle studies have shown, that from the cost point of view, slab tracks might be very competitive.

Tubular Track is a ballast-less railway system with rails continuously supported by means of reinforced concrete beams. This system was originally developed in South Africa, patented and protected as a trade name in South Africa and internationally. With reference to Figure 4.3, Tubular Track System can be described in detail as consisting essentially of two continuous concrete beams held in position by specially designed steel gauge bars. The beam size and reinforcement are designed for each specific project based on the design loads, frequency and the geotechnical conditions of the area the line has to traverse. The beam is cast by pumping concrete grout into the long geotextile sleeves which is slid over the pre-fixed reinforcement. The system has gauge bars consisting of galvanised steel sections welded to steel gussets and straps which encircle the beams. The rails are fastened to the straps using standard fastenings. The system also utilises other railway components applicable to all international gauges, rail sizes and axle loads. The advantages and disadvantages of this design option are discussed in Table 4.3.

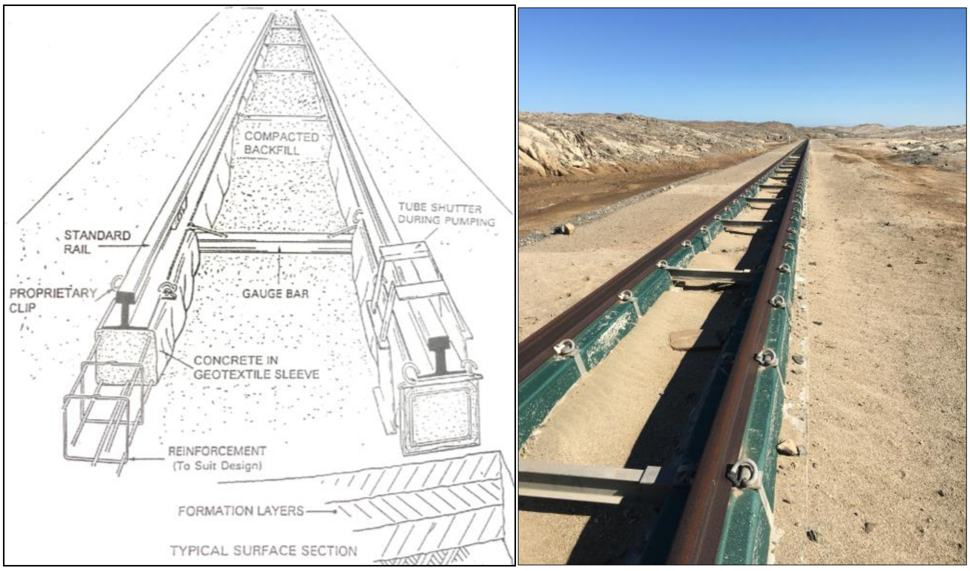

Figure 4.3: Tubular Track System on the Aus-Lüderitz Railway Line [30]

Table 4.3: Advantages and Disadvantages of Tubular Track System - Sand Removal by Hands

Advantages	**Disadvantages**
Design Option 2: Tubular Track System - Sand Removal by Hands	
Tubular Track system is ideal for the railway line passing through the wind-blown sandy desert because there is no ballast fouling compared to the conventional track system.	This solution does not prevent the sand to be blown and deposited onto railway line. Dynamic sand dunes and some severe sand storms crossing the railway line may at times completely cover the line and may affect train operations.

The initial investment costs of this system are lower compared to the conventional track system.	Maintenance and operating costs are very high. It is cumbersome though manageable to carry out this operation by machinery working on the track. Furthermore, machinery may cause damages to the components of the track.
This slab track has a long-life span, hence reduced costs on rehabilitations or renewals.	The most serious drawback of the ballast-less track is that possibilities to repair the slab in case of any damage is costly. If there is a derailment causing any damage to the concrete structure, it will take time and more costs to repair the damaged concrete component(s).
Tubular Track has a lower maintenance cost than the Conventional Ballasted Track, and hence low life cycle costs.	High operation cost for the machinery, especially the replacement and repair of machinery parts due to dust and sand fines. Break downs of machinery is high due to the inclement weather of persistent wind blowing carrying sand particles.
The sand removal operation on this system is quick and it is easy to work around the railway line compared to the ballasted track system.	The system acts as a barrier to airflow carrying sand particles. It, therefore, allows air to deposit sand onto the track and builds up forming dunes over the railway line.
Continuously supported rails have a great reduction in adverse dynamic rail stresses, and lighter rail sections can thus be used. Stresses due to wheel loads are able to dissipate along the beam instead of being concentrated under a discrete sleeper support as the case of a ballasted track system.	
Stability of the track alignment is one of the great advantages of Tubular Track. The geometric stability is greatly enhanced. Track geometry remains constant throughout the life span of the railway.	

No ballast required, hence no stone quarries or tamping costs, and no ballast spillage down narrow embankments.	
Tracks can be completely backfilled to allow vehicular access over tracks.	
Precast panels enable track to be laid quickly, this means immediate track availability.	
Formation stresses are much lower consequently reduced formations width which gives a significant savings in earthworks costs.	

4.2.3. Conventional Track - Sand Removal by Machinery

For the safe and efficient operation of ballasted rail tracks, proper maintenance guidelines to keep ballast layer clean and freely draining are of paramount importance. Sand removal by machinery is a maintenance solution where sand accumulation is hauled away from the track and its close vicinity by machinery such as special on-track machines, bull-dozer, front-end-loader, skid-steer loader (bob-cat), etc. As with sand removal by manual labour, equipment and costs to remove sand differ depending on whether the track is ballasted or a concrete slab track. The results of this study revealed that removing sand by on a ballasted track is costly compared to the slab track because once the ballast is contaminated with sand it requires screening with as special screening machine. The maintenance of these equipment on a harsh condition of this area is very costly. Figure 4.4 illustrates the sand removal operations by machinery. On the Aus-Lüderitz Railway Line mechanical bulldozers were then used for the removal of sand from the tracks. This mechanical operation caused in places severe damage to the track components, thus creating an even greater burden on the track maintenance operation. Continuous mechanical breakdowns of plant due to the harsh on-site weather conditions also makes the sand removal operation difficult. The advantages and disadvantages of this design option are discussed in Table 4.4.

Figure 4.4: Different On-Track Sand Removing Machinery

Table 4.4: Advantages and Disadvantages of Conventional Track - Sand Removal by Machinery

Advantages	**Disadvantages**
Design Option 3. Conventional Track - Sand Removal by Machinery	
All the benefits outlined in Design Option 1 (Ballasted Track (Conventional Track)) are true for this alternative solution. The only difference is that with this option, the removal of sand is done by machinery.	All the implications as set in Design Option 1 (Ballasted Track (Conventional Track)) are true for this alternative solution. The only difference is that with this option, the removal of sand is done by machinery.
Sand removal by machinery is fast and a lot of sand can be removed from the railway line and the surroundings.	Ballast cleaning machinery and the operation as well as plant maintenance is expensive.

4.2.4. Tubular Track System - Sand Removal by Machinery

This system has several advantages over the conventional railway track system including cost and performance benefits especially on railway lines passing through wind-blown sand deserts. As illustrated in Figure 4.5, this system is currently used on the Aus-Lüderitz Railway Line for a route length of 133 km with Continuously Welded Rails (CWR), in the effort to mitigate the problem of sand because with this system there is no fouling of ballast in sandy environment since there is no ballast.

Figure 4.5: Sand Removal by Machinery on the Aus-Lüderitz Railway Line

In the case of conventional track system, ingress of sand onto the track contaminates ballast consequently reducing the structural performance of the track superstructure in transferring loads from the rails into the formation layers. Continuously supported rails on a Tubular Track System mean reduced rail stresses and lighter rail sections/profiles can thus be used, example 30 kg/m can be used for the 18.5 axle loads as used for the first 24 km of track from Aus. Since the track is rigid, the track geometry remains constant through the life of the railway. The advantages and disadvantages of this design option are discussed in Table 4.5.

Table 4.5: Advantages and Disadvantages of Tubular Track System - Sand Removal by Machinery

Advantages	Disadvantages
Design Option 4: Tubular Track System - Sand Removal by Machinery	
All the benefits outlined in Design Option 3 (Ballast-less Track (Tubular Track System)) are true for this alternative solution. The only difference is that with this option, the removal of sand is done by machinery.	All the implications of this system outlined in Design Option 3 (Ballast-less Track (Tubular Track System)) are true for this alternative solution. The only difference is that with this option, the removal of sand is executed by machinery.
Tracks can be completely backfilled to allow vehicular access over tracks and this makes the sand cleaning operations by machinery much	

easier.	

4.2.5. Humped Slab Track (Ballast-less)

A humped slab track is a special track design of a superstructure which offers an efficient solution for mitigating the problems of railways traversing through wind-blown sandy desert areas. It is a ballast-less track system with elevated seats designed with suitable spaces under the rails and between the ‘‘humps’’ which permits airflow as illustrated in Figure 4.6.

Figure 4.6: Humped Slab Track System [24]

In other words, the rails are supported at higher levels on the humps and the flow of sand is allowed to pass through the open channels like a fluid. The free airflow transports sand across the track and keeps the contact area of the rail and wheel virtually free from highly abrasive sand. This helps in prolonging the life span of the rolling stock and the rails. The higher wind velocities permit the wind to carry sand and deposit it across the track. Because of the concrete slab on this system, the maintenance costs are reasonably low since there is no ballast fouling. The advantages and disadvantages of this design option are discussed in Table 4.6.

Table 4.6: Advantages and Disadvantages of Humped Slab Track (Ballast-less)

Advantages	**Disadvantages**
Design Option 5: Humped Slab Track (Ballast-less)	
All the advantages of the Ballast-less Track (Tubular Track System) discussed above also applies for the Humped slab track.	All the drawbacks of the Ballast-less Track (Tubular Track System) discussed above also applies for the Humped slab track.
This solution is much better than the Tubular Track System because it permits the flow of wind carrying sand and deposit it over the railway line.	In as much as this system prevents some sand to be deposited onto the railway line, in case of strong wind storms moving big dunes as observed in the study area, it may not prevent the sand covering the railway line.
This alternative has a longer life span and the operating, maintenance and rehabilitation costs are very low, hence low Life Cycle Cost.	The initial investment cost of this option is slightly high compared to the Tubular Track System.
The maintenance, rehabilitation and operating costs are considerably reduced compared to other solutions that do not permit airflow over the track and act as barriers.	
Reduced rail wears (vertical and lateral wear of the rail head) due to reduced accumulation of sand particles between the rail crown and the contact wheel of the train units. This means reduced maintenance of the rolling stock.	

4.2.6. Humped Ballasted Track (Pedestal Concrete Sleepers)

This system is similar to the humped slab track described in Section 4.2.5. The Humped Ballasted Track was tested in Namibia in 1999 on TransNamib Holding Ltd (TNHL) railway network between Swakopmund and Walvis Bay. A section of 80 m of a special design of rail seats, elevated with help of ‘‘humps’’ on the ballast imbedded ties, was installed with sleepers manufactured by Grinaker (South Africa), refer to Figure 4.7.

Figure 4. 7: Humped Ballasted Track on the Swakopmund-Walvis Bay Railway Line

The Humped Ballasted Track was designed with elevated rail seats (“humps”) to forming a free channel between the top-of-ballast and the bottom of the rail foot. Such a free channel provides a free jet-like opening for the wind to blow through. The rail was elevated by 100 mm creating openings between the ties of some 30,000 mm^2 [25]. Due to the reduced cross-section, the wind velocity will be higher than in the upper layers and needs to accelerate respectively. This higher wind velocities enable the wind to carry sand with it. This test has proven that the section worked most successfully over many years. The observation done over the years demonstrated a sand-free track section, while adjacent sections quickly became overblown and needed repeated labour for clearing the track [25]. However, this system has more maintenance cost compared to the humped slab track due to ballast always contaminated with sand and needs to be cleaned by screening. The advantages and disadvantages of this design option are discussed in Table 4.7.

Table 4.7: Advantages and Disadvantages of Humped Ballasted Track

Advantages	Disadvantages
Design Option 6: Humped Ballasted Track (Pedestal Concrete Sleepers)	
This solution is much better than the Conventional Track System because it permits the flow of wind carrying sand and deposit it over the railway line.	Because the special humped sleepers used in this system are raised, it is difficult for the normal tamping machine to access the ballast layer. If possible, a special or modified tamping tines should be used, and this may be expensive.
The maintenance, rehabilitation and operating costs are considerably reduced compared to other solutions that do not permit airflow over the track and act as barriers.	In as much as this system prevents some sand to be deposited onto the railway line, in case of strong wind storms moving big dunes as observed in the study area, it may not prevent the sand covering the railway line.
Reduced rail wears (vertical and lateral wear of the rail head) due to reduced accumulation of sand particles between the rail crown and the contact wheel of the train units. This means reduced maintenance of the rolling stock.	
All the benefits of the Ballasted Track (Conventional Track System) outlined above also applies for the Humped Ballasted Track constructed with raised pedestal concrete sleepers.	All the drawbacks of the Ballasted Track (Conventional Track System) discussed above also applies for this system.

4.2.7. Conventional Track - Sand Shelter Tunnel System

The section of the railway line heavily affected by sand dunes and that worth sheltering with the tunnel is along the sand belt crossing the railway line on a width of about 4.4 km from km 294,100 to km 298,500 (reference mark from Seeheim (0 km)) (see Locality Plan in Figure 1.1). The tunnel is proposed to be constructed with roofs of circular segments, resting on vertical walls with top slabs, to reduce earth pressure and bottom slabs, connected with horizontal beams for load transfer into the ground, see Figure 4.9 below. Incorporated in the design are all safety measures and regulations, set by TNHL and other statutory bodies. This includes the freeboard to either side of the train, escape refuges at 50 m intervals and provisions for mechanical ventilation of the tunnel [22, 14]. The investment and operating costs of the ventilation system are also included in the cost estimates of the tunnel solution. The proposed basic cross section of the tunnel is shown in Figure 4.8.

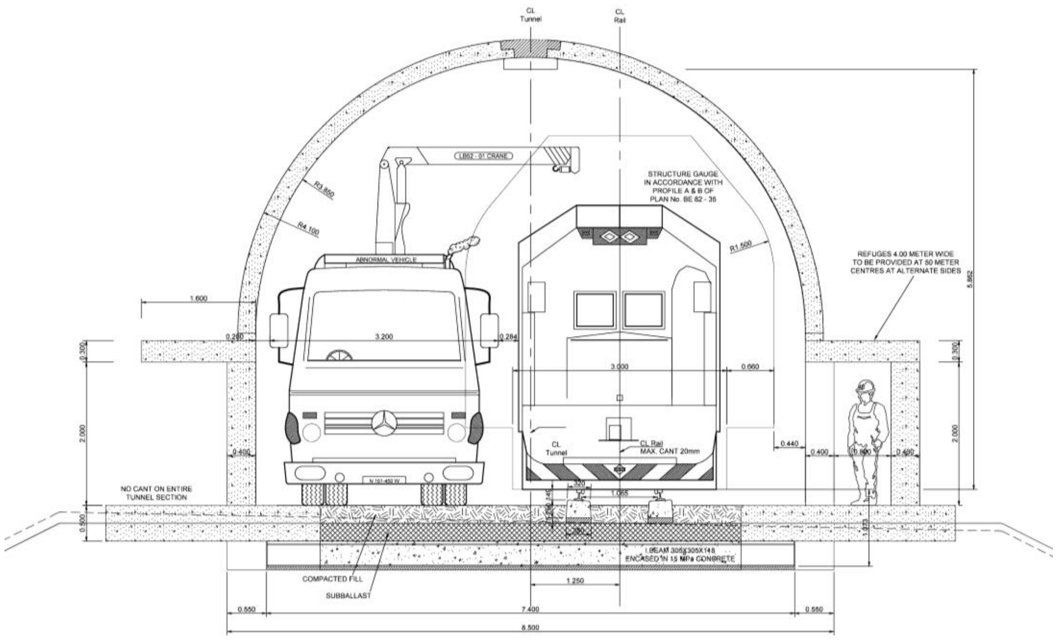

Figure 4.8: Tunnel Cross Section Proposed on the Aus-Lüderitz Railway Line [14]

The individual construction elements of the proposed tunnel system are manufactured as reinforced pre-cast and in-situ concrete components. The extreme high horizontal forces created by dune sand, submerging parts of the tunnel and accumulating to the top of the structure, are transferred by arches of the tunnel roof, through the walls into the sub-structure. The vertical walls of the structure consist of floor slabs and cross beams in the formation layer. Top slabs of the walls create a reduction of the horizontal forces and relieve the load onto the tunnel arches [14].

Foundation beams and slabs, as well as the supporting walls and top slabs are proposed to be constructed in-situ, whereas the top supporting beams and the tunnel roof segments will be pre-cast in a factory, assembled and connected with high strength concrete on site. The vertical walls of the tunnel are connected by steel beams, encased in concrete, thus distributing the horizontal forces into the two bottom foundation slabs (left and right). The friction between foundation slabs and formation is sufficient to prevent horizontal displacement of the tunnel segment. Top beams are required for positioning the roof segments and have after hardening of the concrete infills between walls, arches and on top between the individual roof segments, no further structural function. See the tunnel model in Figure 4.9 showing the tunnel segments described above.

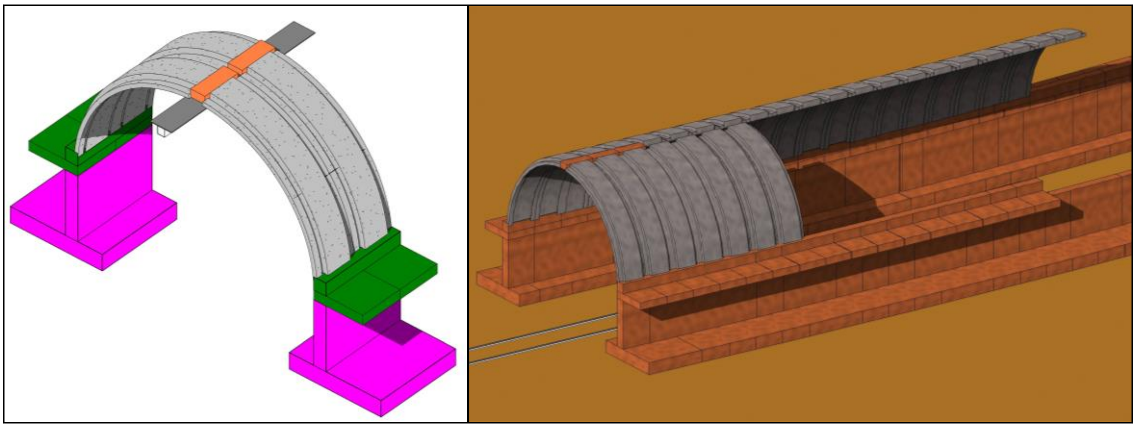

Figure 4.9: Proposed Tunnel Model

The pre-manufactured shell segments, with a thickness of 250 mm and a width of 1.20 meter are provided with an outside groove of 125 mm, to enable joining and adjustment with the adjacent elements [22]. The tunnel shell segments will be positioned with a gap onto the sidewalls and on the top beams, from both sides at a time. After positioning, the segments are joined together and with the top beam, with cast in-situ concrete. Due to the chemical aggressive environment at the coast, it will be necessary to locate the plant for the manufacture of the pre-cast elements further inland. A proposed suitable construction site, for establishing the manufacturing plant for the pre-cast elements, has been located at Haalenberg Railway Station (see to Figure 1.1), some 35 km inland from Lüderitz. The advantages and disadvantages of this design option are discussed in Table 4.8.

Table 4.8: Advantages and Disadvantages of Conventional Track – Sand Shelter Tunnel System

Advantages	**Disadvantages**
Design Option 7: Conventional Track – Sand Shelter Tunnel System	
The maintenance and operating costs are reduced.	The initial investment, maintenance and operating costs of the tunnel structure is very high compared to all other components of other alternatives. The tunnel cost component resulted in this option to have high investment costs.
This solution prevents the deposit of wind-blown sand onto railway line by sheltering the railway line with the tunnel structure. Dynamic sand dunes and some severe sand storms crossing the railway line cannot affect train operations.	If there is any omission of ballast in placing, this has a significant implication in terms of the construction costs and the longer-term maintenance costs.
No trains delay due to sand problems because the railway is sheltered under tunnel structure. The railway line is always available, safe, hence reliable.	Loss of geometric stability is a challenge for ballasted track. Ballast spreads and settles resulting in the loss of vertical and horizontal alignment.
No contamination of ballast by sand. The structural ability or the performance of the track superstructure is enhanced.	Loss of track resilience resulting from ballast degrading and becoming contaminated. This results into increased dynamic damage to the track structure (corrugations) as well as to the rolling stock.
The availability, reliability and the safety of the line is guaranteed. Night train movements may be not restricted.	Ballast requires regular tamping cycles and cleaning and/or replacement at a shorter rehabilitation period. Inevitably some damage is caused to other components of track system

	during tamping.
Reduced rail wears (vertical and lateral wear of the rail head) due to the absence of sand particles between the rail crown and the contact wheel of the train units. This means reduced maintenance of the rolling stock.	Pumping of sub-ballast layer caused by dynamic loading, results in ballast fouling from below and destruction of formation.
Working in the harsh condition of strong wind-blown sand which poses health hazard to the labourers is eliminated.	Ballasted track has higher noise level than non-ballasted track. It is necessary to take effective noise reduction measures.
All benefits of the Ballasted Track (Conventional Track System) outlined in previous alternatives discussed above are also true for this alternative solution.	Ballasted track has a low life span, the rehabilitation or renewal has to be done in short intervals compared to a slab track.
	TransNamib's diesel electric locomotives emits a large amount of polluting exhaust gases, which are very harmful to the travellers, train operation crew and the maintenance workers in the tunnel, especially when a train stops in the tunnel. Therefore, efficient continuous ventilation system in the tunnel is required, which is very complex and expensive. The ventilation system is also included in this LCCA.
	Due to the changing wind directions at the tunnel portals, the tunnel is exposed to sand fills to be removed on regular basis and to always ensure that the portals are clear of sand.
	It is difficult to work in the tunnel in case of a derailment or train collision in the tunnel.
	The sand shelter tunnel structure is large, and it may not be aesthetically pleasing.

4.2.8. Tubular Track System – Sand Shelter Tunnel System

The factors such as extended service life, low maintenance, availability and capacity for increased speeds and axle loads, etc. made the ballast-less track system to be more attractive to be using in tunnels. Life cycle cost considerations discussed in this study clearly reveal the advantages of ballast-less designs. The advantages and disadvantages of this design option are discussed in Table 4.9.

Table 4.9: Advantages and Disadvantages of Tubular Track System - Sand Shelter Tunnel System

Advantages	Disadvantages
Design Option 8: Tubular Track System - Sand Shelter Tunnel System	
Maintenance and operating costs are reduced. Working in the harsh condition of strong wind-blown sand which poses health hazard to the labours is eliminated.	The initial investment, maintenance and operating costs of the tunnel structure is very high compared to all other components of other alternatives. The tunnel cost component resulted in this option to have high investment costs.
This alternative provides good solutions to the sand problem because it eliminates the chances of sand deposits and accumulation on the railway line. This solution prevents the deposit of wind-blown sand onto railway line by sheltering the railway line with the tunnel structure. Dynamic sand dunes and some severe sand storms crossing the railway line cannot affect train operations. Potential derailment is reduced.	The most serious drawback of the ballast-less track is that possibilities to repair the slab in case of any damage is costly. If there is a derailment causing any damage to the concrete structures, it will take time and more costs to repair the damaged concrete component(s).
No trains delay due to sand problems because the railway is sheltered under tunnel structure. The railway line is always available, safe, hence reliable.	TransNamib's diesel electric locomotives emits a large amount of polluting exhaust gases, which are very harmful to the travellers, train operation crew and the maintenance workers in the tunnel, especially when a train stops in the tunnel. Therefore, efficient continuous

	ventilation system in the tunnel is required, which is very complex and expensive. The ventilation system is also included in this LCCA.
Tubular Track is ideal for the tunnel where poor drainage and tamping/re-ballasting difficulties are very problematic for conventional track.	Due to the changing wind directions at the tunnel portals, the tunnel is exposed to sand fills to be removed on regular basis and to always ensure that the portals are clear of sand.
Night train movements may be not restricted, which means the availability, reliability and the safety of the line is guaranteed.	It is difficult to work in the tunnel in case of a derailment or train collision in the tunnel.
Reduced rail wears due to the absence of sand particles between the rail crown and the contact wheel of the train units. This means reduced maintenance of the rolling stock and reduced potential of derailment.	The sand shelter tunnel structure is large, and it may not be aesthetically pleasing.
All the benefits of the Ballast-less Track (Tubular Track System) outlined in previous alternatives discussed above are also true for this solution.	

4.3. Estimated Costs of Different Design Options

Costs considered in the analysis are all real costs incurred directly by the agencies over the whole life span of the alternative solution. The costs typically involved initial investment costs, user costs (operating costs (O_c) and maintenance costs (M_c)) and rehabilitation costs. Table 4.10 shows the estimated costs of all the alternatives considered in this study. It is important to note that all costs are estimated per km length of track. The estimated cost data for construction were based upon the current averaged tendered rates, operating and maintenance cost estimates were mostly obtained from TNHL officials, and other costs were drawn from historical records and engineering judgements by experts.

Table 4.10: Estimated Costs of Different Design Options

Design Option	Initial Investment Cost (1000 N$)		Total Initial Investment Cost (1000 N$)	Operating Cost per Annum (1000 N$)	Maintenance Cost per Annum (1000 N$)	Operating + Maintenance Cost (1000 N$) per Annum	Rehabilitation Cost (1000 N$) @ Rehab. Years Interval
	Design	Construction					
1. Conventional Track (Hands)	333.50	6,670.00	**7,003.50**	572.73	2,236.36	**2,809.09**	**2,267.80**
2. Tubular Track (Hands)	249.00	4,980.00	**5,229.00**	409.09	804.55	**1,213.64**	**1,693.20**
3. Conventional Track (Machinery)	333.50	6,670.00	**7,003.50**	640.91	4,909.09	**5,550.00**	**1,400.70**
4. Tubular Track (Machinery)	249.00	4,980.00	**5,229.00**	409.09	2,727.27	**3,136.36**	**1,045.80**
5. Humped Slab Track (Ballast-less)	323.70	6,474.00	**6,797.70**	318.18	579.55	**897.73**	**1,359.54**
6. Humped Ballasted Track (Pedestal Concrete Sleepers)	383.53	7,670.50	**8,054.03**	409.09	2,236.36	**2,645.45**	**1,610.81**
7. Conventional Track- Sand Shelter Tunnel System	333.50	6,670.00	**7,003.50**	372.27	1,453.64	**1,825.91**	**1,400.70**
8. Tubular Track System - Sand Shelter Tunnel System	249.00	4,980.00	**5,229.00**	265.91	522.95	**788.86**	**1,045.80**
Tunnel Structure for both Design Option 7 & 8	5,500.00	110,000.00	**115,500.00**	163.64	204.55	**368.18**	**11,550.00**
Note: All costs are per km length of track.							

Figure 4.10 presents the Expenditure Stream Diagram for the initial investment cost, rehabilitation cost and the Salvage and RSL Value of Design Option 1. As demonstrated in Figure 4.10, other costs can also be presented in the similar format and this may also be carried out for all the design options. Generally, costs are represented as upward arrows at the suitable time they transpire during the analysis period, and benefits are shown as negative cost or downward arrows. The benefits of providing mitigation measures to the problem of wind-blown sand covering the track are considered to be the same for all alternatives outlined. Both RSL and the salvage value were regarded as negative costs and are subtracted from the estimated costs of their respective alternatives. Both values are very important to account for in the analysis to prevent being bias towards one or another alternative solution. As a result, the only concerns are the differential costs between alternatives. Under these conditions, the LCCA objective is strengthened to finding the alternative solution that meets the requirements of mitigating sand ingress into the track at the lowest life cycle cost.

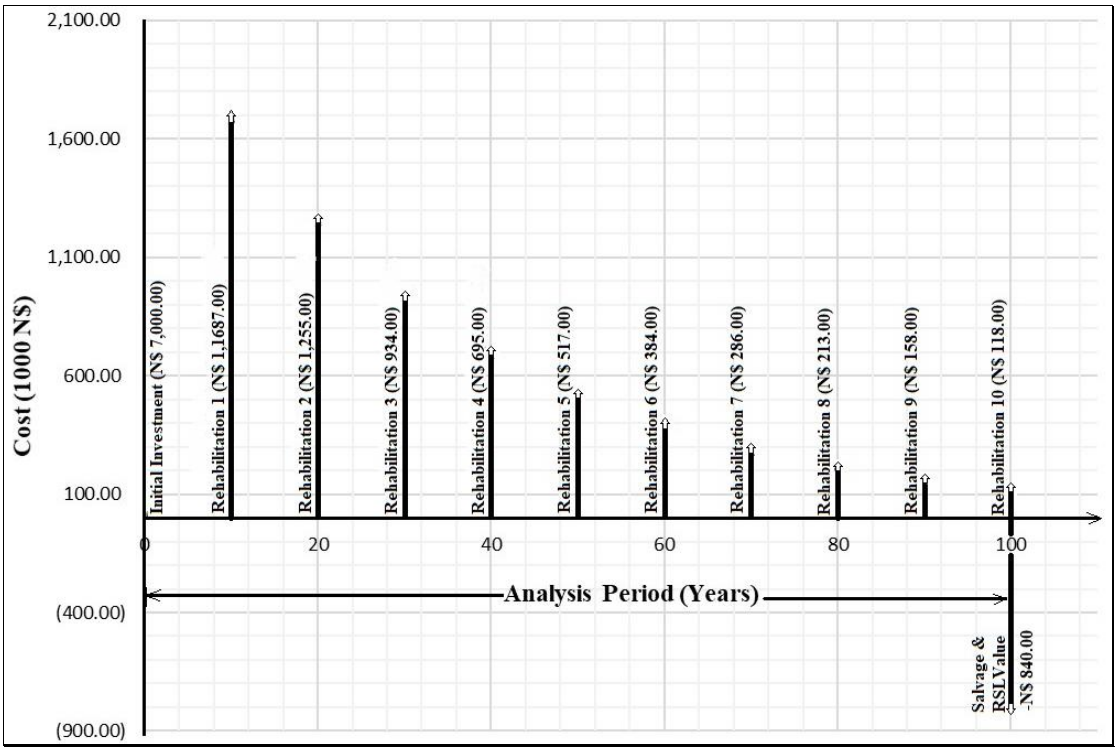

Figure 4.10: Expenditure Stream Diagram - Design Option 1

4.4. Results of the Life Cycle Cost Analysis

The LCCA value is also sometimes referred to as the NPV in this study. The NPV for each alternative solution was computed based on the general expression, given in Equation 3.1 section 3.5 of Chapter 3 of this study. The NPV was used to discount separate future amounts at various time intervals stipulated in the maintenance and rehabilitation plan until the end of the analysis period of the alternative. The LCCA detailed results of all alternatives are presented in Table B1 to B8 under Appendix B. The summary of these results is presented in Table 4.11.

Table 4.11: Summary of the LCCA Results

Design Options	Life Cycle Cost (1000 N$)
1. Conventional Track (Hands)	**103,987.00**
2. Tubular Track (Hands)	**45,999.00**
3. Conventional Track (Machinery)	**190,948.00**
4. Tubular Track (Machinery)	**107,917.00**
5. Humped Slab Track (Ballast-less)	**35,881.00**
6. Humped Ballasted Track (Pedestal Concrete Sleepers)	**95,528.00**
7. Conventional Track- Sand Shelter Tunnel System	**184,884.00**
8. Tubular Track System - Sand Shelter Tunnel System	**149,006.00**

Note: All costs are per km length of track and in 1000 N$.

4.5. Sensitivity Analysis for the LCCA Results

Table 4.12 shows the direct comparison of the NPV of all the alternative solutions with different discount rates (2, 3, 4, 5 and 6%). The results of this analysis are also shown graphically in Figure 4.11. The results of the LCCA shows the NPV of all the alternative solutions decreasing as the discount rate increases. The main reason for this is because of the reduced present value of future costs at higher discount rates. The effect of the discount rate is totally different for each alternative solution mainly due to time period of the rehabilitation, and the costs of future maintenance and operating cost. The results of this sensitivity analysis revealed that alternative 3, the sand removal by machinery on the ballasted track (conventional track), is the most expensive solution to undertake and alternative 5 to be the cheapest option throughout at all discount rates. Furthermore, alternative 3 and 5 have also revealed to be the highest and lowest respectively, at the considered discount rate (3%). It is noteworthy to highlight that the results of the this LCCA and the sensitivity analysis revealed that a ballasted track is more expensive than the ballast-less especially under a harsh condition such as this of a wind-blown sandy desert. The initial investment, maintenance and operating the cost of the ballast-less track are low compared to those of the ballasted track.

Table 4.12: Sensitivity Analysis to Discount Rate

Design Options	Discount Rate (%)				
	2	3	4	5	6
	1000 N$				
1. Conventional Track (Hands)	138,965	103,987	82,438	68,305	58,511
2. Conventional Track (Machinery)	60,967	45,999	36,792	30,763	26,591
3. Ballast-less Track (Hands)	256,422	190,948	150,575	124,079	105,706
4. Ballast-less Track (Machinery)	144,608	107,917	85,298	70,459	60,172
5. Humped Slab Track (Ballast-less)	46,856	35,881	29,135	24,719	21,666
6. Humped Ballasted Track (Pedestal Concrete Sleepers)	127,138	95,528	76,029	63,231	54,358
7. Conventional Track - Sand Shelter Tunnel System	220,343	184,884	163,174	149,011	139,240
8. Tubular Track System - Sand Shelter Tunnel System	172,203	149,006	134,856	125,654	119,323

Note: All costs are per km length of track and in 1000 N$.

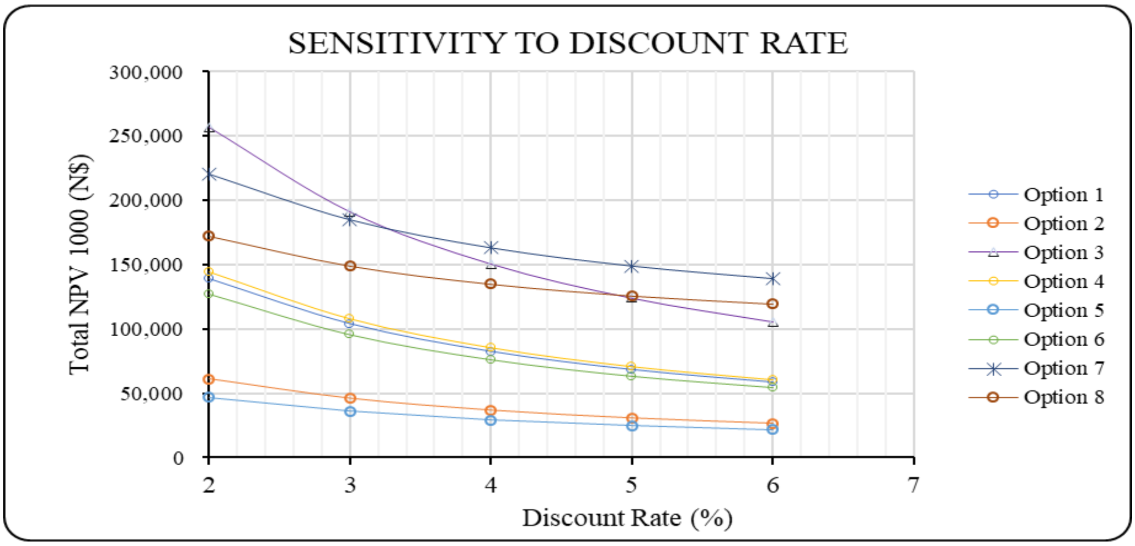

Figure 4.11: Sensitivity Analysis of NPV to Discount Rate

The main disadvantages of this approach are that it does not analyse the input data simultaneously nor give any estimation of the likelihood of the occurrence of the input value. In addition to these drawbacks, despite this approach giving considerable sufficient information about the economic effectiveness of an alternative solution rather than just its initial cost, it does not offer decision-makers a complete information of the anticipated LCCA values, and generally the analysis gives equal weight to any input value assumptions, regardless of the likelihood of occurring.

4.6. Life Cycle Cost Analysis

The factors influencing the performance of this railway line section were identified and assessed in order to estimate the LCCA of the alternative solutions. The findings of this study have provided the means to evaluate and compare the costs and benefits of different alternatives. All the decisions related to the railway track maintenance and rehabilitation were considered in order to optimise the analysis between the safety and the economic aspects of the whole railway system. The main aim is to ensure that the railway line is available because the main issue on this line is the accumulation of desert sand that hinders the train movements and ultimately affecting the availability, safety and the reliability of the line. It is not an easy task to assess the technical life period of the track, in this adverse weather condition of strong wind carrying desert sand, because it is highly dependent on a lot of other external factors that one may hardly access and estimate correctly, such as the railway traffic volume (frequency) and the axle loading (tonnage). However, this was finally projected from the capacity and logistic operational plans of the Port of Lüderitz. In addition to this, the combination of railway components with different life expectance are cumbersome to determine and tie them into a single service life period for the purpose of the analysis.

Detailed discussion of the benefits and implications of the alternative solutions revealed that sand removal both by hand and machinery, humped slab and ballasted track does not prevent sand ingress into the railway line. These alternatives are, therefore, not effective for the section of the line where high dynamic dunes are crossing the railway line as it is the case on the dune belt crossing the Aus-Lüderitz Railway Line for the width approximately 4.4 km (track centreline length) between km 294,100 and 298,500. These solutions are only effective on the rest of the sections of this railway line where the sand accumulation does not get high than 300 mm from top of rail.

The LCCA revealed that the options utilising ballast (ballasted conventional and humped track system) have high LCCA due to high maintenance and rehabilitation costs as compared to ballast-less (slab) track options. The cost estimates also showed that the initial investment costs of the ballasted track (Conventional Track System) are relatively high compared to the initial costs of the ballast-less track (Tubular Track System). In the analysis, Tubular Track System was assessed to be cost-effective compared to the Conventional Track System. The LCCA for this study further revealed that in the whole analysis the Humped Slab Track system is the cheapest options evaluated. Therefore, based on the results presented, analysed and discussed, it can be unpacked that the Humped Slab Track system is the most cost-effective solution evaluated to be ideal for the sections of the railway line where no sand dunes are experienced and where the sand accumulation on the track does not exceed 300 mm high from top of rail.

Based on the LCCA of this study, the Tubular Track system sheltered by the concrete tunnel structure showed attractive LCCA results for a dune belt section where high dunes persist. As noted in the literature reviewed, this dune belt has been posing problems to the railway infrastructure maintenance and operation over years. The engineers, and railway infrastructure managers have been seeking for the best solution to this problem. Recently it was finally proposed to erect the sand shelter tunnel to house the railway track across the dynamic dunes belt. Among other alternatives explored through test models and trial sections as reviewed in the literature, the tunnel system was recommended to be the only solution to mitigate this problem on the dunes belt section. The tunnel system is the only solution that has proven to allow un-interrupted flow of traffic across the sand dune belt on the Aus-Lüderitz Railway Line, thereby guaranteeing the reliability, availability, maintainability and the safety of the railway system. On the other sections along this line, where sand accumulation is not severe as to the sand dune belt section, the Humped Slab Track system revealed to be the most cost-effective solution to consider, based on the LCCA carried out.

4.7. Summary

This chapter was mainly concerned with the presentation, analysis and discussion of results and findings of the research. It started with the presentation and analysis of the identified design and maintenance solutions appropriate to mitigate the problem of wind-blown sand on the railway line. The chapter has attempted to explore the benefits and implications of these design options and maintenance strategies. The chapter further described in detail the LCCA parameters used to undertake the study. The importance of the discount rate on the LCCA was apprehended in this study, its details and bases of choice were, therefore, discussed. The LCCA results of the study has provided a good insight into the costing parameters of different alternatives explored to mitigate the sand ingress onto the railway line. The chapter was rounded off by discussing the most effective and convenient solution(s) in the long run based on the LCCA results achieved. The next chapter will conclude this research study and give recommendations.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In the Namibian Railway Network, the Aus-Lüderitz and Swakopmund-Walvis Bay Railway Line are traversing through the Namib Desert. It is presented in this study that the wind-blown sand poses a great challenge to this railway lines. The sand clogs the track resulting in the stoppage of train operations for safety reasons and mostly because the railway lines are not available. Maintenance and operating costs are reported to be very high due to this problem. The problem of sand invasion onto the track hinders the safe and reliable operations, reduces the availability, and increases the maintenance frequency of the railway line. The main objective of this study is to use LCCA, as an engineering economic tool, to determine the cost-effectiveness of the options to the challenging wind-blown sand on the railway lines passing through the desert. Specific objectives are: 1) Identify the best infrastructure design options and technical maintenance solutions for mitigating the sand problem onto the tracks. 2) Use the LCCA to evaluate the cost-effectiveness of the different solutions in order to recommend the best strategy. Ultimately the LCCA was employed in the study, as an engineering economic technique, to determine the cost-effectiveness and viability of the solution(s) to combat the challenge of sand ingress onto the railway line. The study has proven that the LCCA can be used to identify cost-effective design options for railway lines through sand blown areas.

In the LCCA process, different alternatives were identified, which includes both railway infrastructure design solutions and technical mitigation measures. Specifically, analysed and discussed alternatives were Sand Removal by Hand on the Ballasted (Conventional Track) and Ballast-less (Tubular Track), Sand Removal by Machinery on the Ballasted

(Conventional Track) and Ballast-less (Tubular Track), Humped Slab Track, Humped Ballasted Track (Pedestal Concrete Sleepers) and finally the Ballasted (Conventional Track) and Ballast-less (Tubular Track) system sheltered in a concrete Sand Shelter Tunnel Structure.

The LCCA results presented the Humped Slab Track to be the cost-effective solution compared to all other alternatives. However, this solution does not prevent the accumulation of sand especially during sand storms that frequently happens on the dune belt crossing the railway line with high dunes. It was, therefore, discussed that this option is only ideal for the rest of the sections where dunes are not crossing. This has proven that in as much as LCCA is a good engineering economic tool, it needs to be coupled with viability criterion/criteria in order to determine the cost-effectiveness of the design and maintenance solutions to combat the challenging problem of wind-blown sand on the railway line passing through desert areas. The study further proved that Tubular Track system was cost-effective compared to the Conventional Track system. The study provides a good insight of analysis to prove that Tubular Track system covered in the Tunnel System is the most viable and cost-effective solution to the sand problem along the dune belt. The study can be concluded that the ultimate objective of the study was achieved by using the LCCA as an engineering economic tool to determine the cost-effectiveness of the viable solutions to combat the challenging problem of wind-blown sand on the railway line passing through desert areas. The LCCA technique results were used in this study as the basis of selecting the best alternative solution to mitigate the problem.

5.2. Recommendations

The LCCA in this study provides a rational framework for information regarding different costs to be incurred, effects and the benefits of different alternative solutions proposed. Based on the findings from this study there are a number of key recommendations for the industry and for further studies. The following are the recommendations developed from this research:

- The Government of the Republic of Namibia (GRN), TNHL and other public entities should develop an integrated LCCA database for different projects they are undertaking, to assist in data collection for future studies. In addition, the use of the database is always valuable in promoting improved management planning and control. The LCCA is highly dependent on the quality of input data used, it is therefore considerable to ensure that sufficient and good information is used to compute the LCCA.

- Due to the uncertainties associated with the estimation and assumptions of variable costs and other related parameters made during the LCCA, a sensitivity analysis is mostly important to address the variability and the uncertainty linked with the LCCA input data. In this study, a simple deterministic approach was used, and it does not analyse the input data simultaneously nor give any estimation of the likelihood of the occurrence of the input value. It is, therefore, recommended that a probabilistic approach that is more powerful to overcome the drawbacks of the deterministic approach, be used in future studies to analyse the LCCA results. With the power and sophistication of today's computers and software, simulation techniques such as Monte Carlo are recommended for incorporating variability associated with LCCA inputs into final results, to brand uncertainty.

- The unforeseen or indirect costs such as delay costs, environmental costs, etc., should be modelled and incorporated in the LCCA to make the estimation of costs more effective. These costs are not simulated in this study, therefore future studies should integrate them into the analysis. The indirect costs associated with each alternative are difficult to measure, however, they are very significant to the LCCA. As the world is moving towards environmentally friendly railway system, it is of outmost importance to estimate the costs due to pollution and environment damages and be included in the LCCA computation.

- Upon the implementation of the most viable and cost-effective solution to mitigate sand problem, it is recommended to undertake an evaluation study to determine performance of the improvement(s). It involves the collection of data for a period of time after the implementation to ascertain whether the anticipated benefits are actually attained. Therefore, a further study on the review of the performance of railway system is very crucial to validate and further justify the importance, need and desirability of the LCCA.

- The last recommendation is for the Namibian industry to foster interest in helping academic researchers by providing them with the information they need, where ever possible, as part of their corporal social responsibility and public relations.

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APPENDICES

APPENDIX A: Maintenance and Rehabilitation Strategies and Timings

Table A 1: Maintenance and Rehabilitation Strategies and Timings

Alternative	Routine Maintenance Activities	Periodic Maintenance Timing of Asset (Years) [10]	Periodic Maintenance Activities	Rehabilitation Timing of Asset (Years) [10]	Rehabilitation Activities
1. Conventional Track (Hands)	Rails Grinding, Tamping, Inspection, Sand Cleaning, Track Inspection, repair of latent defects and faults	5	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning, Ballast cleaning, Track geometrical Checks.	10	Renewal of railway components (Sleepers, ballast, fasteners, rails, etc.), formations where and when required.
2. Tubular Track (Hands)	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning, Track Inspection, repair of latent defects and faults	10	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning, Track geometrical Checks.	20	Renewal of railway components (gauge bars where required, fasteners, rails, etc.), grout formations repair and renewal where and when required.
3. Conventional Track (Machinery)	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning, Track Inspection, repair of latent defects and faults	5	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning, Ballast cleaning, Track geometrical Checks.	10	Renewal of railway components (Sleepers, ballast, fasteners, rails, etc.), formations where and when required.
4. Tubular Track (Machinery)	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning, Track Inspection, repair of latent defects and faults	10	Rails Grinding, Trolley Inspection & Patrol, Sand Cleaning, Ballast cleaning, Track geometrical Checks, removal of defective panels.	20	Renewal of railway components (fasteners, defective panels, rails, etc.), formations where and when required
5. Humped Slab Track (Ballast-less)	Rails Grinding, Trolley Inspection & Patrol, Sand Cleaning, Track Inspection	10	Rails Grinding, Trolley Inspection & Patrol, Sand Cleaning, Track geometrical Checks.	25	Renewal of railway components (gauge bars where required, fasteners, rails, etc.), grout formations repair and renewal where and when required.
6. Humped Ballasted Track (Pedestal Concrete Sleepers)	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning, Track Inspection	5	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning, Ballast cleaning, Track geometrical Checks.	15	Renewal of railway components (Sleepers, ballast, fasteners, rails, etc.), formations where and when required.
7. Conventional Track- Sand Shelter Tunnel System	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning on the portals, Track Inspection	5	Rails Grinding, Tamping, Trolley Inspection & Patrol, Sand Cleaning, Ballast cleaning, Track geometrical Checks.	20	Renewal of railway components (Sleepers, ballast, fasteners, rails, etc.), formations where and when required.
8. Tubular Track System - Sand Shelter Tunnel System	Rails Grinding, Trolley Inspection & Patrol, Sand Cleaning on the portals, Track Inspection	10	Rails Grinding, Trolley Inspection & Patrol, Sand Cleaning on the portals, Track Inspection	25	Renewal of railway components (gauge bars where required, fasteners, rails, etc.), grout formations repair and renewal where and when required.
Tunnel Structure for both Design Option 7 & 8	Tunnel Inspection, Sand Cleaning on the portals and the escape routes, mechanical ventilation maintenance, cleaning and repair of mechanical and electrical components	5	Tunnel Inspection, Sand Cleaning, Sand Cleaning on the portals, renewal of concrete surfaces; cleaning, repair & replacement of mechanical & electrical components (jet fans, Control components, lights, control room components etc.).	10	Renewal of tunnel concrete surfaces, replacement of electrical & mechanical components (jet fans, Control components, lights, control room etc.), grout and panels with defects.

APPENDIX B: Life Cycle Cost Analysis Results

Table B1: Design Option 1 LCCA Results

Discounting Rate = 3%				10 Years Rehab Interval		
1. Conventional Track - Sand Removal by Hands						
	Factor	0.03				
Years (n)	**(1+*i*)^(-n)**	**Mc+Oc (1000 N$)**	**(1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Cummulative (1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**
0	1.000	2,809	2,809.09			
1	0.971		2,727.27		2,268	
5	0.863		2,423.15	15,674		
10	0.744		2,090.23	11,097		1,687.46
15	0.642		1,803.05	9,573		
20	0.554		1,555.33	8,257		1,255.63
25	0.478		1,341.64	7,123		
30	0.412		1,157.31	6,144		934.30
35	0.355		998.30	5,300		
40	0.307		861.15	4,572		695.21
45	0.264		742.83	3,944		
50	0.228		640.77	3,402		517.30
55	0.197		552.74	2,935		
60	0.170		476.80	2,531		384.92
65	0.146		411.29	2,184		
70	0.126		354.78	1,884		286.42
75	0.109		306.04	1,625		
80	0.094		263.99	1,402		213.12
85	0.081		227.72	1,209		
90	0.070		196.43	1,043		158.58
95	0.060		169.45	900		
100	0.052		146.16	776		118.00
Sum				**91,573.29**		**6,250.94**
(Mc+Oc & Rehab) Sum			97,824.23			
Total Initial Investment Cost (1000 N$)			7,004			
Salvage & RSL Value (1000 N$)			(840.42)			
TOTAL LCC (1000 N$)			**103,987.31**			

Table B2: Design Option 2 LCCA Results

Discounting Rate = 3%				20 Years Rehab Interval		
2. Tubular Track System - Sand Removal by Hands						
	Factor	0.03				
Years (n)	**(1+*i*)^(-n)**	**Mc+Oc (1000 N$)**	**(1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Cummulative (1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**
0	1.000	1,214	1,213.64			
1	0.971		1,178.29		1,693	
5	0.863		1,046.89	6,772		
10	0.744		903.06	4,794		
15	0.642		778.99	4,136		
20	0.554		671.96	3,568		937.48
25	0.478		579.64	3,077		
30	0.412		500.00	2,655		
35	0.355		431.31	2,290		
40	0.307		372.05	1,975		519.06
45	0.264		320.93	1,704		
50	0.228		276.84	1,470		
55	0.197		238.80	1,268		
60	0.170		205.99	1,094		287.39
65	0.146		177.69	943		
70	0.126		153.28	814		
75	0.109		132.22	702		
80	0.094		114.05	606		159.12
85	0.081		98.38	522		
90	0.070		84.87	451		
95	0.060		73.21	389		
100	0.052		63.15	335		88.10
Sum				**39,563.22**		**1,991.16**
LCC (Mc+Oc & Rehab) Sum			41,554.38			
Total Initial Investment Cost (1000 N$)			5,229			
Salvage & RSL Value (1000 N$)			(784.35)			
TOTAL LCC (1000 N$)			**45,999.03**			

Table B3: Design Option 3 LCCA Results

Discounting Rate = 3%				10 Years Rehab Interval		
3. Conventional Track - Sand Removal by Machinery						
	Factor	0.03				
Years (n)	**(1+*i*)^(-n)**	**Mc+Oc (1000 N$)**	**(1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Cummulative (1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**
0	1.000	5,550	5,550.00			
1	0.971		5,388.35		1,401	
5	0.863		4,787.48	30,967		
10	0.744		4,129.72	21,925		1,042.25
15	0.642		3,562.33	18,913		
20	0.554		3,072.90	16,314		775.53
25	0.478		2,650.71	14,073		
30	0.412		2,286.53	12,139		577.07
35	0.355		1,972.38	10,472		
40	0.307		1,701.39	9,033		429.39
45	0.264		1,467.63	7,792		
50	0.228		1,265.99	6,721		319.51
55	0.197		1,092.06	5,798		
60	0.170		942.02	5,001		237.75
65	0.146		812.59	4,314		
70	0.126		700.95	3,721		176.90
75	0.109		604.65	3,210		
80	0.094		521.57	2,769		131.63
85	0.081		449.91	2,389		
90	0.070		388.10	2,060		97.95
95	0.060		334.78	1,777		
100	0.052		288.78	1,533		72.88
Sum				**180,923.92**		**3,860.87**
LCC (Mc+Oc & Rehab) Sum			184,784.80			
Total Initial Investment Cost (1000 N$)			7,004			
Salvage & RSL Value (1000 N$)			(840.42)			
TOTAL LCC (1000 N$)			**190,947.88**			

Table B4: Design Option 4 LCCA Results

Discounting Rate = 3%				20 Years Rehab Interval		
4. Tubular Track System - Sand Removal by Machinery						
	Factor	0.03				
Years (n)	**(1+*i*)^(-n)**	**Mc+Oc (1000 N$)**	**(1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Cummulative (1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**
0	1.000	3,136	3,136.36			
1	0.971		3,045.01		1,046	
5	0.863		2,705.45	17,500		
10	0.744		2,333.75	12,390		
15	0.642		2,013.11	10,688		
20	0.554		1,736.53	9,219		579.03
25	0.478		1,497.94	7,953		
30	0.412		1,292.14	6,860		
35	0.355		1,114.61	5,918		
40	0.307		961.47	5,105		320.60
45	0.264		829.38	4,403		
50	0.228		715.43	3,798		
55	0.197		617.13	3,276		
60	0.170		532.34	2,826		177.51
65	0.146		459.21	2,438		
70	0.126		396.11	2,103		
75	0.109		341.69	1,814		
80	0.094		294.75	1,565		98.28
85	0.081		254.25	1,350		
90	0.070		219.32	1,164		
95	0.060		189.19	1,004		
100	0.052		163.19	866		54.42
Sum				102,242.02		**1,229.84**
LCC (Mc+Oc & Rehab) Sum			103,471.86			
Total Initial Investment Cost (1000 N$)			5,229			
Salvage & RSL Value (1000 N$)			(784.35)			
TOTAL LCC (1000 N$)			**107,916.51**			

Table B5: Design Option 5 LCCA Results

Discounting Rate = 3%				25 Years Rehab Interval		
5. Humped Slab Track (Ballast-less)						
	Factor	0.03				
Years (n)	**(1+*i*)^(-n)**	**Mc+Oc (1000 N$)**	**(1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Cummulative (1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**
0	1.000	898	897.73			
1	0.971		871.58		1,360	
5	0.863		774.39	5,009		
10	0.744		667.99	3,546		
15	0.642		576.22	3,059		
20	0.554		497.05	2,639		
25	0.478		428.76	2,276		649.32
30	0.412		369.85	1,964		
35	0.355		319.04	1,694		
40	0.307		275.20	1,461		
45	0.264		237.39	1,260		
50	0.228		204.78	1,087		310.12
55	0.197		176.64	938		
60	0.170		152.37	809		
65	0.146		131.44	698		
70	0.126		113.38	602		
75	0.109		97.80	519		148.12
80	0.094		84.37	448		
85	0.081		72.77	386		
90	0.070		62.78	333		
95	0.060		54.15	287		
100	0.052		46.71	248		70.74
Sum				29,264.93		**1,178.30**
LCC (Mc+Oc & Rehab) Sum			30,443.23			
Total Initial Investment Cost (1000 N$)			6,798			
Salvage & RSL Value (1000 N$)			(1,359.54)			
TOTAL LCC (1000 N$)			**35,881.39**			

Table B6: Design Option 6 LCCA Results

Discounting Rate = 3%				15 Years Rehab Interval		
6. Humped Ballasted Track (Pedastal Concrete Sleepers)						
	Factor	0.03				
Years (n)	**(1+*i*)^(-n)**	**Mc+Oc (1000 N$)**	**(1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Cummulative (1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**
0	1.000	2,645	2,645.45			
1	0.971		2,568.40		1,611	
5	0.863		2,281.99	14,761		
10	0.744		1,968.47	10,451		
15	0.642		1,698.02	9,015		1,033.91
20	0.554		1,464.72	7,776		
25	0.478		1,263.48	6,708		
30	0.412		1,089.89	5,786		663.63
35	0.355		940.15	4,991		
40	0.307		810.98	4,306		
45	0.264		699.56	3,714		425.96
50	0.228		603.45	3,204		
55	0.197		520.54	2,764		
60	0.170		449.02	2,384		273.41
65	0.146		387.33	2,056		
70	0.126		334.11	1,774		
75	0.109		288.21	1,530		175.49
80	0.094		248.61	1,320		
85	0.081		214.46	1,139		
90	0.070		184.99	982		112.64
95	0.060		159.57	847		
100	0.052		137.65	731		
Sum				86,238.92		**2,685.04**
LCC (Mc+Oc & Rehab) Sum			88,923.96			
Total Initial Investment Cost (1000 N$)			8,054			
Salvage & RSL Value (1000 N$)			(1,449.72)			
TOTAL LCC (1000 N$)			**95,528.26**			

Table B7: Design Option 7 LCCA Results

Discounting Rate = 3%			25 Years Interval - Track			10 Years Interval - Tunnel Structure		
7. Conventional Track – Sand Shelter Tunnel System								
	Factor	0.03			**Track**		**Tunnel Structure**	
Years (n)	**(1+*i*)^(-n)**	**Mc+Oc (1000 N$)**	**(1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Cummulative (1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**
0	1.000	1,826	1,825.91					
1	0.971		1,772.73		1,401		11,550	
5	0.863		1,575.05	10,188				
10	0.744		1,358.65	7,213				8,594.28
15	0.642		1,171.98	6,222				
20	0.554		1,010.96	5,367		775.53		6,394.95
25	0.478		872.06	4,630				
30	0.412		752.25	3,994				4,758.45
35	0.355		648.90	3,445				
40	0.307		559.74	2,972		429.39		3,540.73
45	0.264		482.84	2,563				
50	0.228		416.50	2,211				2,634.64
55	0.197		359.28	1,907				
60	0.170		309.92	1,645		237.75		1,960.42
65	0.146		267.34	1,419				
70	0.126		230.61	1,224				1,458.73
75	0.109		198.92	1,056				
80	0.094		171.59	911		131.63		1,085.44
85	0.081		148.02	786				
90	0.070		127.68	678				807.67
95	0.060		110.14	585				
100	0.052		95.01	504		72.88		600.98
Sum				59,522.64		**1,647.19**		**31,836.29**
LCC (Mc+Oc & Rehabs) Sum			93,006.11					
Total Initial Investment Cost (1000 N$)			122,504					
Salvage & RSL Value (1000 N$)			(30,625.88)					
TOTAL LCC (1000 N$)			**184,883.74**					

Table B8: Design Option 8 LCCA Results

Discounting Rate = 3%			25 Years Interval - Track			10 Years Interval - Tunnel Structure		
8. Tubular Track System - Sand Shelter Tunnel System								
	Factor	0.03			**Track**		**Tunnel Structure**	
Years (n)	**(1+*i*)^(-n)**	**Mc+Oc (1000 N$)**	**(1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Cummulative (1+*i*)^(-n) (Mc+Oc) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**	**Rehab (1000 N$)**	**(1+*i*)^(-n) (Rehab) (1000 N$)**
0	1.000	789	788.86					
1	0.971		765.89		1,046		11,550	
5	0.863		680.48	4,402				
10	0.744		586.99	3,116				8,594.28
15	0.642		506.34	2,688				
20	0.554		436.77	2,319				6,394.95
25	0.478		376.77	2,000		499.48		
30	0.412		325.00	1,725				4,758.45
35	0.355		280.35	1,488				
40	0.307		241.83	1,284				3,540.73
45	0.264		208.61	1,108				
50	0.228		179.95	955		238.55		2,634.64
55	0.197		155.22	824				
60	0.170		133.90	711				1,960.42
65	0.146		115.50	613				
70	0.126		99.63	529				1,458.73
75	0.109		85.94	456		113.93		
80	0.094		74.14	394				1,085.44
85	0.081		63.95	340				
90	0.070		55.16	293				807.67
95	0.060		47.58	253				
100	0.052		41.05	218		54.42		600.98
Sum				25,716.09		**906.39**		**31,836.29**
LCC (Mc+Oc & Rehabs) Sum			58,458.76					
Total Initial Investment Cost (1000 N$)			120,729					
Salvage & RSL Value (1000 N$)			(30,182.25)					
TOTAL LCC (1000 N$)			**149,005.51**					