APPLICATION OF THE LIFE CYCLE COST ANALYSIS TECHNIQUE TO EXPLORE DESIGN AND MAINTENANCE SOLUTIONS FOR RAILWAY LINES IN WINDBLOWN SANDY DESERTS: THE AUS-LÜDERITZ RAILWAY LINE CASE STUDY

J HAMALWA, PT JOHANNES and R AMBUNDA*

University of Namibia, Department of Civil and Mining Engineering, PO Box 3624, Ongwediva, Namibia; *Email: rambunda@unam.na

ABSTRACT

The operation and maintenance of railway lines built in sandy deserts in Namibia are significantly affected by the deposit of windblown sand on the railway lines. This has necessitated the need to explore robust and economically justifiable technical solutions to mitigate the sand problem on railway lines, to ensure reliability, availability, and safety performance. The challenge for decision-makers has been a lack of context-developed infrastructure design options and technical maintenance solutions to sustainably address this challenge. The rationale of this study was to determine the cost-effectiveness of different rail design and maintenance options to address the challenge of windblown sand on railway lines passing through the Namib Desert, by applying the life cycle cost analysis (LCCA) method, as an engineering economic tool. The study identified and reviewed multiple designs and technical maintenance solutions using the LCCA method to determine and recommend the most cost-effective and best-practice strategy to mitigate the adverse consequences of sand deposits on railway lines. The study identified the humped slab track as the most viable solution for railway sections where the dune belts do not cross the railway line. On sections where strong sandstorms frequently cause the accumulation of sand on the railway lines, the LCCA results found the Tubular Track (TT) system as the most viable and cost-effective solution compared to other options.

Keywords: Life cycle cost analysis, railways, infrastructure, windblown sand, Namibia.

1. INTRODUCTION AND BACKGROUND

Railway transport in Namibia is one of the most important modes of transport with great importance to the economy of the country. Railway lines are the most economical, efficient, environmentally friendly, and safe solution for long-distance transportation of heavy goods (Patra, 2009). Owing to the significant mining and industrial sector, Namibia considers railways as an optimal transportation mode for heavy goods over long distances. Railways can accommodate heavier loads compared to road transport without causing damage to the permanent way or infrastructure. As such, the rail system is a preferred choice for the transportation of heavy goods in the country. Namibia's railway network currently stretches from south to north, with a middle line to the east and links to coastal towns such as Swakopmund, Walvis Bay and Lüderitz (Dierks, 2004). Both the Swakopmund-Walvis Bay and the Aus-Lüderitz railway line pass through the Namib Desert, where at some sections the windblown sand is problematic for maintenance and operations (Bruno et al., 2018a; Dierks 2004; Raffaele & Bruno, 2019a). Sandstorms frequently deposit large amounts of sand onto the rail track (Horvat et al., 2021), which necessitates ongoing efforts to remove dunes of varying sizes from the track to maintain clear lines.

2. PROBLEM STATEMENT

The Aus-Lüderitz railway line is vulnerable to constant windblown sand which affects the efficiency and functionality of the line (Mehdipour & Baniamerian, 2019; Raffaele & Bruno, 2019a). The harsh nature of the windblown sand clogging tracks may stop train operations for safety reasons (Zhang et al., 2022). This infamous dune belt with its ever-shifting dunes has been an enormous burden to the railway authorities in maintaining and operating these lines. The continuous invasion of the sand onto the track remains an unsolved problem in Namibia. This problem hinders safe and reliable operations, reduces availability, and increases maintenance frequency (Raffaele & Bruno, 2020; Zakeri, 2012). There are different solutions to mitigate the problem of windblown sand on railway lines, which are railway infrastructure design solutions and technical mitigation measures. However, the challenge for decision-makers is the identification of a cost-effective solution for implementation. Decision-makers are, therefore, expected to explain and justify decisions concerning the expenditure of the taxpayer's money on such infrastructure investments (Farran & Zayed, 2012; Zoeteman, 2001). A common method to evaluate the cost-effectiveness of different solutions is by using the LCCA approach (Ciszewski & Nowakowski, 2018; Innovation Track System, 2006; Rama & Andrews 2016; U.S. Department of Transportation, 1998; Zoeteman, 2001). The need for infrastructure owners and operators to ensure high operational performance of infrastructure at an optimal cost has stimulated the utility of LCCA tools (Ciszewski & Nowakowski, 2018; Farran & Zayed 2012; Matos et al., 2018). According to Fourie & Tendayi (2016) and Patra (2009), the LCCA method is an important engineering economic tool for decision-makers. It helps in identifying the most cost-effective investment option, thereby assisting in making optimal economic decisions. This ensures that the railway infrastructure is reliable, available, maintainable, and safe at minimal costs (Al-Douri et al., 2016).

3. OBJECTIVES

This study aims to use the LCCA method to determine the cost-effectiveness of different solutions to mitigate the challenging windblown sand on railway lines passing through the desert. The following specific objectives are set:

- To identify the best infrastructure design options and technical maintenance solutions to mitigate the sand problem onto tracks.
- To evaluate the cost-effectiveness of different solutions by using the LCCA method.

4. SCOPE OF THE STUDY

This study was mainly focused on the LCCA method of the railway infrastructure passing through the windblown sand Namib Desert on the Aus-Lüderitz railway line in Namibia. The study was confined to a 10 km section between the 290 and 300 km chainage, where the dune belt crosses the railway line. This is the only section along this route where sand deposition varies in volume and size, which helps in mapping all the potential solutions to the same area for comparison purposes.

5. LITERATURE REVIEW

5.1 The Aus-Lüderitz Railway Line

5.1.1 History of Aus-Lüderitz Railway Line

According to Bravenboer & Rusch (1999), the Aus-Lüderitz railway line was built during the colonial era in 1906. The design of the line was approved in May 1905 in Berlin with the recommendation to erect corrugated sheet tunnels at least 100 m long each at five different places along the dune belt section of the route to mitigate the settlement of shifting sand on the tracks (Bravenboer & Rusch, 1999). 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 (Dierks, 2004). Thereafter, the line was used to carry passengers and freight, and for the import and export of general merchandise through the Lüderitz harbour (Dierks, 2004). The railway administration, however, found it difficult to maintain the line through the years, particularly to keep the line clear of the dune sand on the section crossing the dune belt near Lüderitz. This line was de-commissioned in 1997 mainly due to aged tracks and recurring costs of removing frequent windblown sand across the track by the strong winds (K&A Consulting Engineers, 2018).

5.1.2 Upgrading of the Aus-Lüderitz Railway Line

The rehabilitation of this line started in 2000 and was completed at the end of 2017. The total length of the rehabilitated line is 139.5 kms, entirely through the Namib Desert. The line was upgraded from 11.5 tonnes to 18.5 tonnes axle load using both the conventional track and Tubular Track (TT) system. The conventional track system was used on the first section of this line through the desert with 48 kg/m rails on P2 concrete sleepers at 700 mm c/c nominal spacing, 1200 m^3/km ballast (53 mm particle size) and E3131 cast iron chairs and fastenings. The remainder of the section traversing through the windblown sandy desert was constructed using the TT system with 48 kg/m rails (K&A Consulting Engineers, 2018).

5.1.3 Sand Problems on the Tracks

The movement of dunes was and is a present problem for the Namibian railway administration. Bruno et al. (2018a) and Dierks (2004) indicated that the infamous dune belt of the Namib Desert with its ever-shifting sand posed tremendous problems to the railway lines. This does not only pose operational problems but financial burdens to ensure that the line is clear of dune sand (Zakeri, 2012). Major consequences of sand on tracks include increased maintenance and rehabilitation costs, reduced traffic speeds, delays in train operations and safety concerns (Bruno et al., 2018a; Zakeri, 2012). Specific challenges comprise track blockages, ballast ingress/contamination, fouling of electrical systems, and jamming of switches/gearboxes of the railway line. The major issue with sand deposits on the track is ballast fouling which inhibits the structural performance of the track (Zhang et al., 2022) and burying the track under sand makes the railway line unavailable for operations (Raffaele & Bruno, 2019b). Figure 1 shows the TT system in the study area buried under dune sand.

Figure 1: Aus- Lüderitz railway line covered by windblown sand crossing the line

5.2 Railway Design and Maintenance Options

Effective and sustainable mitigation solutions are required to ensure the reliability, availability, maintainability, and safety (RAMS) of the railway line (Bruno et al., 2018a). Sand-resistant measures include ballastless track systems such as the TT system (Figure 2a) and the humped slab track system (Horvat et al., 2021) (Figure 2d). The TT system was used in the study area because of its significant benefits as opposed to the conventional track system (Figure 2e). In harsh desert conditions of frequent wind-driven sand, ballastless track systems (mainly slab track) have low maintenance costs and do not give any problems of ballast fouling (Grabe, 2012). A ballasted railway track built with humped sleepers (pedestal concrete sleepers) (Figure 2b) presented by Rießberger & Swanepoel (2005) is another mitigation measure proven to free rail heads from windblown desert sand (Horvat et al., 2021; Zakeri, 2012).

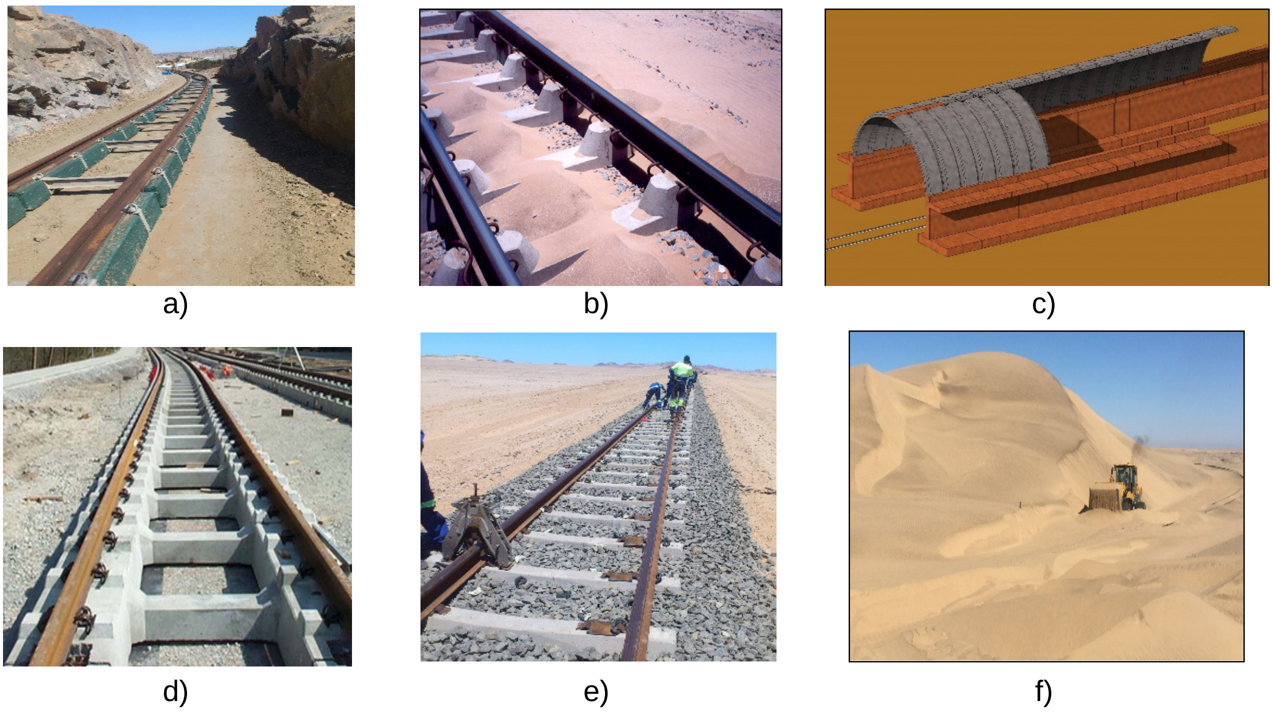


Figure 2: Railway design and maintenance options: a) Tubular Track railway system (ballastless track system) b) Humped ballasted track (Rießberger & Swanepoel 2005) c) Sand shelter tunnel (K&A Consulting Engineers 2018) d) Humped slab track (ballastless) e) Conventional track system f) Sand removal by machinery

Some railway maintenance solutions such as the removal of sand from the track by manpower (manual labour) and mechanical means (sand removing machinery) (Figure 2f), and mechanical and chemical dune stabilisation are among considerable options in desert areas (Watson, 1985; Zakeri, 2012).

Avoidance of sand deposits on the track may also be done with fencing and sand barriers (Bruno et al 2018b; Horvat et al., 2020; Xin et al., 2021). Covering the railway line with the sand shelter concrete tunnel (Figure 2c) is another effective windblown sand mitigation measure that avoids sand deposits on the track (Bravenboer & Rusch, 1999; Horvat et al., 2021).

5.3 Life Cycle Cost Techniques

In the transport economics context, the LCCA method can be defined as an economic evaluation technique applicable to the consideration of certain transportation investment decisions by calculating the total cost of a system or a product over its total life span (Galar et al., 2017; Innovation Track System 2006; U.S. Department of Transportation, 2002). This tool is used to compare the total cost of different options (Giunta et al., 2018). The LCCA method can be described as a technique for evaluating and quantifying the total economic value of options by accounting and analysing initial costs, discounting future costs, that is, operating, maintenance, and rehabilitation costs, and the salvage value of the infrastructure, over its life span (Ciszewski & Nowakowski, 2018; Giunta et al., 2018; Sasidharan et al., 2020). According to Fourie and Tendayi (2016), the desirable implementation plan is the one with the lowest total costs over the entire lifespan of the infrastructure. Many methods can be employed to carry out an economic evaluation of transportation projects. The commonly used methods include the Present Worth (PW) also known as Total Present Value (TPV) or Net Present Value (NPV), Equivalent Uniform Annual Cost (EUAC), Benefit Cost Ratio (BCR) and Internal Rate of Return (IRR) (de Charmoy & Gräbe, 2020; Sasidharan et al., 2020; Zoeteman, 2001). This study used the PW method.

6. METHODOLOGY

This section describes how the research was undertaken. The main aim of the section is to explicitly report on how data was obtained, and the procedures used to determine the LCCA and how the results were analysed. Technical input data and information were gathered, and an economic assessment was performed.

6.1 Life Cycle Cost Analysis

The procedural steps of the LCCA method can be summarised in Table 1, using descriptions that have been adapted from the U.S. Department of Transportation (2002).

Table 1: Summary of methodology for LCCA

Step	Description
1	Establish Design Options
2	Determine Performance Periods and Activity Timing ▪ *Service Life and Analysis Period of Design Options* ▪ *Activity Planning and Timing*
3	Estimated Costs of Different Design Options
4	Compute Life Cycle Costs
5	Analyse the Results

Adapted from U.S. Department of Transportation, 2002

These steps are further described in subsequent sections.

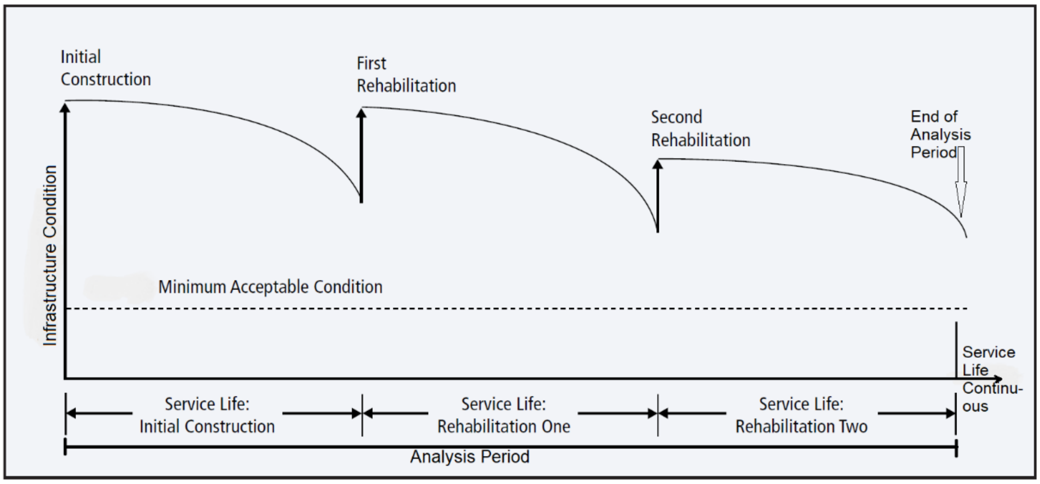
Step 1: Establish design options

The LCCA method starts with the establishment of options to mitigate the problem of windblown sand on the railway line. Windblown sand mitigation measures differ in several ways, which include the planning and design; initial investment, operation, and maintenance costs. Implementation of different measures to mitigate windblown sand on transportation infrastructures requires a thorough knowledge of the behaviour of wind-sand flow (Mehdipour & Baniamerian, 2019).

Step 2: Determine performance periods and activity timing

a) Service life and analysis period of design options

Alternative design solutions have different service lives, which is the time frame the infrastructure is available for normal good use to serve its purpose. Performance life period prediction was determined based on the design life of solutions, and maintenance and rehabilitation of solutions under review (U.S. Department of Transportation, 2002). A common analysis period of 100 years was used throughout as a base period to assess cost differences between competing options (Kaewunruen et al., 2020). The analysis period in this study was made long enough to ensure that at least one major rehabilitation activity for each option was covered. The assumption of the service life of an option does not necessarily mean that the structure will no longer be fit for its purpose at the end of the analysis period. This means that the service life continues beyond the end of the analysis period depending on the condition of the infrastructure (see Figure 3).



(Adapted from U.S. Department of Transportation 2002)

Figure 3: Analysis period of a design option

b) Activity planning and timing

For all options developed, individual maintenance and rehabilitation strategic plan was developed after identifying the maintenance and rehabilitation activities required for each option. The maintenance and rehabilitation plan made it easier for the analyst to schedule when future maintenance and rehabilitation activities should be carried out, for how much, when and for how long. Each option has several rehabilitation and maintenance intervals expected due to the age and use of the infrastructure (Patra, 2009). The prevailing weather condition to which the various options are exposed, that is, coastal weather and strong wind carrying desert sand, and other factors that may lead to the deterioration of the infrastructure were also important factors considered. Deterioration of the infrastructure results in the downfall of the level of performance of the infrastructure (Farran & Zayed, 2012). It is, therefore, of paramount importance to carry out periodic maintenance and rehabilitation activities to improve and maintain the quality, performance, and safety of the infrastructure.

Step 3: Estimated costs of different design options

Costs typically include initial investment costs, operating costs, maintenance costs, rehabilitation costs and disposal costs (Giunta et al., 2018; Kaewunruen et al., 2020; Sasidharan et al., 2020). In this cost estimation exercise, only costs that demonstrate differences between options were considered as described by Zoeteman (2003), to simplify the analytical and data requirement considerably. For all options, salvage value and remaining service life value were considered in the cost estimation (Giunta et al., 2018; U.S Department of Transportation, 1998).

Step 4: Compute life cycle costs

By employing a discounting technique, costs are discounted into present values and added up for each option. After all costs and timings for different options were developed and the future costs of each option were discounted to the base year and added to the total initial investment cost to determine the NPV of each option (Galar et al., 2017). The NPV was used to convert the expected future costs to present monetary values so that the life cycle costs of different options may be directly compared.

Step 5: Analyse the results

The LCCA method is highly dependent on the assumptions and estimations made during the analysis or in the process of data collection. The NPV method was used in this study to determine the LCCA to evaluate the time-dependent value of money over the life span of the infrastructure. The expression of NPV also generally used by the U.S. Department of Transportation (2002) is given in Equation 1 below.

$$\mathrm{NPV} = \sum_{n=0}^{n} \left[\frac{1}{(1+i)^n} C_n \right] \tag{1}$$

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 referred to as the 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 the relevant PV factor for the future time (year) under review. The selection of a suitable discount rate *i* is important 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 (Giunta et al., 2018). The discount rate can reflect the effect of the real earning power of money invested over a period or it may also reflect the effects of inflation. The type of costs used in this study are the real costs, therefore real discount rate was also used to compute the LCCA. In the case of public projects which are funded by the government from taxpayer money, the discount rate should be reasonable and consistent with the opportunity cost of the public at large (Giunta et al., 2018). The discount rate assumed for all evaluated options in this study was 3%, based on 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 advantages of the whole national economy and the interest of the whole public at large (Pichler, 2010). After computing the LCCA, it is imperative to address the variability and uncertainties associated with LCCA input data such as activity cost, timing, and discount rate (Kaewunruen et al., 2020). A sensitivity analysis was conducted to identify the impact of the uncertainty of different variables (Giunta et al., 2018). In the sensitivity analysis, major input values varied either within some percentage of the initial value or over a range of values while all other input values remain constant and analyse the variation in results (Kaewunruen et al., 2020).

7. RESULTS AND DISCUSSION

The results and discussion section of this scientific article presents an evaluation of different railway design options based on their estimated costs and LCCA. The section begins by discussing the various design options considered in this study. Subsequently, an in-depth analysis of the estimated costs associated with each design option is provided. Furthermore, a comprehensive LCCA is presented, which includes an assessment of the capital, operating, and maintenance costs associated with each design option. Finally, the sensitivity analysis for the LCCA results to determine the impact of different assumptions on the results is explored. Overall, this section provides a detailed analysis of the cost implications of different railway design options and presents insights that can guide decision-making in railway design and construction.

7.1 Different Railway Design Options

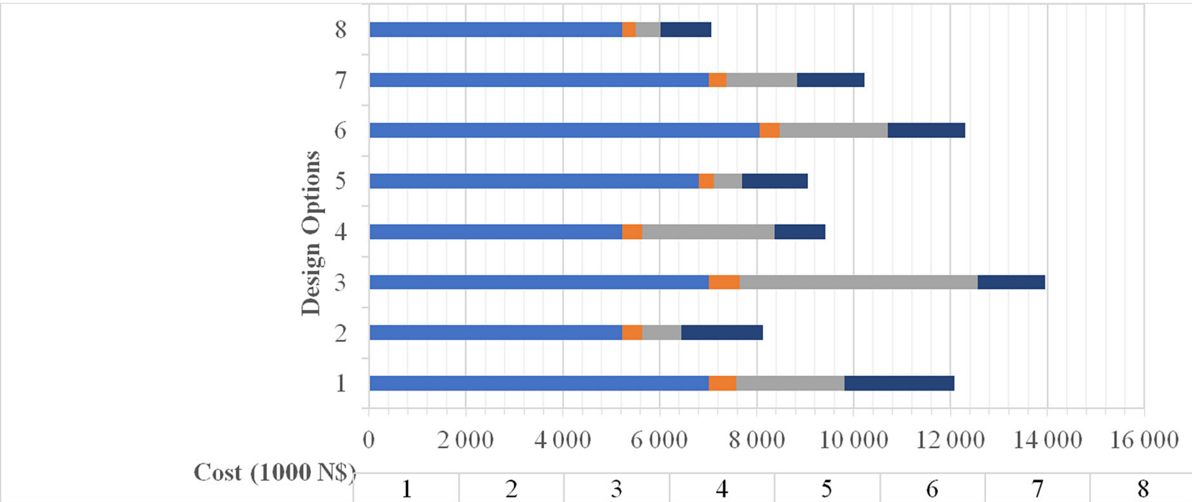
The choice of the appropriate design solutions and the maintenance strategies of the railway line are key factors in the decision-making process for the identification of the most competitive and sustainable solution. Different railway design options and associated technical maintenance solutions to mitigate the sand problem on the tracks identified are tabulated in Table 2.

Table 2: Design options and maintenance solutions to mitigate windblown sand

Design Option	Maintenance Option
1. Conventional track (ballasted track)	Sand removal by hand or manual labour.
2. Tubular track (ballastless track)	Sand removal by hand or manual labour.
3. Conventional track (ballasted track)	Sand removal by machinery.
4. Tubular track (ballastless rack)	Sand removal by machinery.
5. Humped slab track (ballastless)	Self-cleansing, minor sand removal by hand or machinery.
6. Humped ballasted track (pedestal concrete sleepers)	Self-cleansing, minor sand removal by hand or machinery.
7. Conventional track - sand shelter tunnel system	Minor sand removal by either hand (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 hand (manual labour) or machinery on the tunnel escape stations and portals (entrance/exit).

7.2 Estimated Costs of Different Design Options

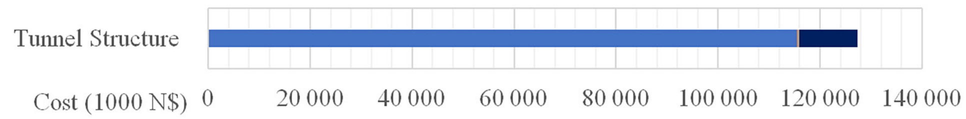
Costs considered in the analysis are all real costs incurred directly by the agencies over the whole life span of the solution. Costs typically involve initial investment costs, user costs (operating costs and maintenance costs) and rehabilitation costs (Fourie & Tendayi, 2016). Figure 4 presents the estimated costs of all options considered in this study. The section of the railway line along the dune belt heavily affected by the windblown sand is worth sheltering with the tunnel. The tunnel would be constructed using reinforced concrete elements considering the aggressive coastal weather and strong desert sandy windstorms. The cost estimates per kilometre length of track of the tunnel structure are presented in Figure 5 and these costs are incorporated into the LCCA of design options 7 and 8 only. The estimated cost data for construction were based upon the current averaged tendered rates. Operating and maintenance cost estimates were mostly obtained from TransNamib Holdings Limited, and other costs were drawn from historical records and engineering judgements by experts. The Namibian Consumer Price Index (CPI) was used in some cases to estimate the costs based on the previous records. All cost estimates in this study were calculated in 2019.



	1	2	3	4	5	6	7	8
Total Initial Investment Cost	7 003,50	5 229,00	7 003,50	5 229,00	6 797,70	8 054,03	7 003,50	5 229,00
Operating Cost per Annum	572,73	409,09	640,91	409,09	318,18	409,09	372,27	265,91
Maintenance Cost per Annum	2 236,36	804,55	4 909,09	2 727,27	579,55	2 236,36	1 453,64	522,95
Rehab. Cost @ Rehab. Years Interval	2 267,80	1 693,20	1 400,70	1 045,80	1 359,54	1 610,81	1 400,70	1 045,80

Figure 4: Estimated costs of different design options (Note: Options 7 and 8 only present costs of the track system)

Figure 4 displays the cost estimate for the track system in options 7 and 8, which does not include the cost of the tunnel structure to present this data. The cost estimate for the tunnel structure is shown separately in Figure 5. However, to analyse the total cost of options 7 and 8 accurately, both the costs of the track system in Figure 4 and the costs of the tunnel structure in Figure 5 must be added together.



	Tunnel Structure
Total Initial Investment Cost	115 500,00
Operating Cost per Annum	163,64
Maintenance Cost per Annum	204,55
Rehab. Cost @ Rehab. Years Interval	11 550,00

Figure 5: Tunnel structure estimated costs

7.3 Life Cycle Cost Analysis

The LCCA value is also sometimes referred to as the NPV in this study. The NPV for each option was computed using the general expression given in Equation 1. The NPV was used to discount separate future amounts at various time intervals until the end of the analysis period of the option. The summary of these results is presented in Figure 6. All costs are per kilometre length of track and in 1000 N$.

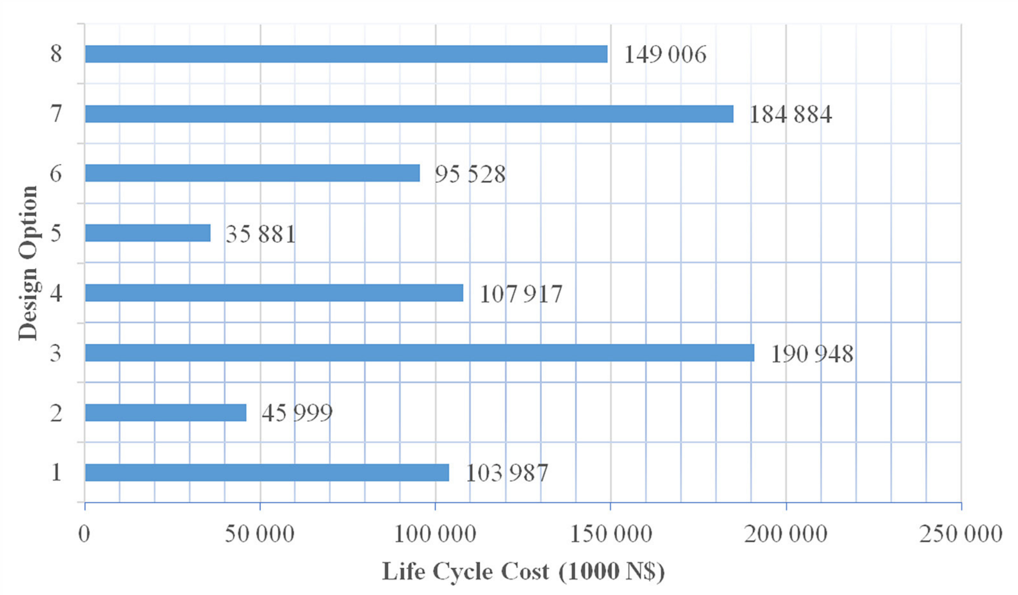


Figure 6: Summary of the LCCA results

Factors influencing the performance of this railway line section were identified and assessed to estimate the LCCA of options. As indicated by Fourie & Tendayi (2016), the choice of the best option is dependent on the most favourable NPV after the LCCA is calculated over the specified period. The findings of this study provided the means to evaluate and compare the costs and benefits of different options. All decisions related to the railway track maintenance and rehabilitation were considered to optimise the analysis considering safety and economic aspects to ensure the availability, safety, and reliability of the line. The maintenance option of sand removal both by hand and machinery does not prevent sand ingress into the railway line. These options are, therefore, not effective for the section of the line where high dynamic dunes are crossing the railway line. These solutions are only effective on the rest of the sections of this railway line where the sand accumulation does not get higher than 300 mm from the top of the rail.

The LCCA method revealed that 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 (TT System). In the same analysis, the TT system was assessed to be cost-effective compared to the Conventional Track System. The LCCA results further revealed that the humped slab track system is the cheapest option evaluated. These results are in line with the findings of Grabe (2012) that ballast-less track is a more attractive option in cases where sand fouling ballast is inevitable and low maintenance cost is required. Based on the results of this study, it can be unpacked that the humped slab track system is the most cost-effective solution evaluated to be ideal for sections of the railway line where no dunes are experienced and where the sand accumulation on the track does not exceed 300 mm high from the top of the rail. Based on the LCCA method of this study, the TT system sheltered by the concrete tunnel structure indicates attractive LCCA results for a dune belt section where high dunes persist. The tunnel system is the only solution that has proven to allow the uninterrupted flow of traffic across the dune belt on the Aus-Lüderitz railway line, thereby guaranteeing the reliability, availability, maintainability, and safety of the railway. Based on the results of the LCCA, it was found that the humped slab track system is the most cost-effective solution to be considered for sections along this line where sand accumulation is not as severe as it is in the dune belt section.

7.3.1 Sensitivity Analysis for the LCCA Results

Figure 7 presents the direct comparison of the NPV of all options with different discount rates (2%, 3%, 4%, 5% and 6%). Results of the LCCA indicate that the NPV of all options is decreasing as the discount rate increases because of the reduced present value of future costs at higher discount rates. Results of this sensitivity analysis revealed that option 3, the sand removal by machinery on the ballasted track (conventional track), is the most expensive solution to undertake until the discount rate of 3.3%. From the discount rate of 3.3% upward, option 7 is the most expensive option. Option 5 is the cheapest option considering all discount rates. Furthermore, options 3 and 5 have also been revealed to be the highest and lowest respectively, at the analysis discount rate (3%). Results of the LCCA and sensitivity analysis revealed that a ballasted track is more expensive than a ballastless, especially under harsh conditions such as this of a windblown sandy desert.

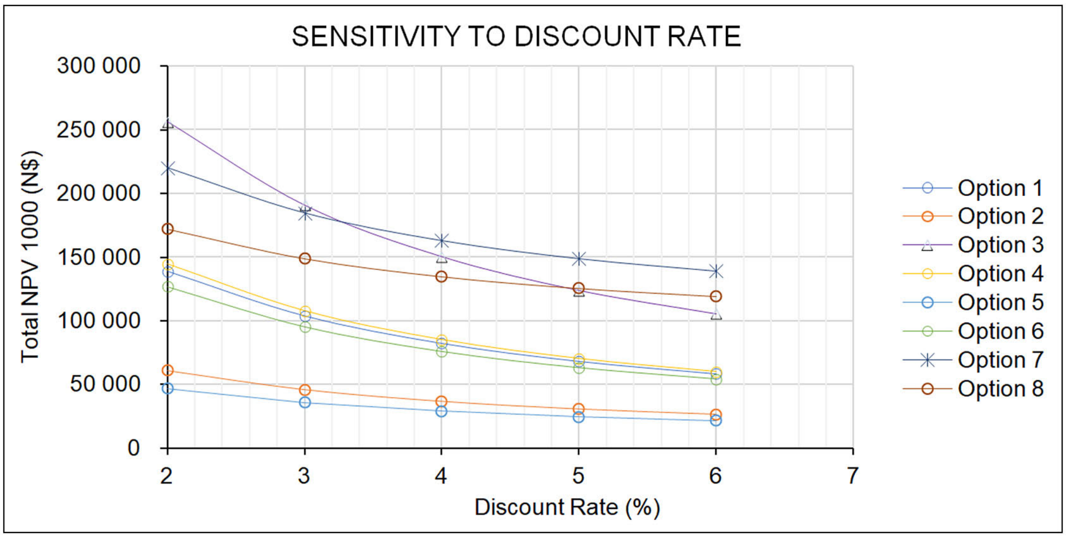


Figure 7: Sensitivity analysis of NPV to discount rate

8. CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

This study indicated that the windblown sand poses a great challenge to the railway lines traversing through the Namib Desert. The sand clogs the track resulting in the stoppage of train operations. Sand invasion onto track hinders the safety and reliability, reduces availability, and increases the maintenance frequency of the railway line. The main purpose of this study was to use the LCCA technique to determine the cost-effectiveness of various options to the challenging windblown sand on railway lines passing through the desert by taking the Aus-Lüderitz railway line as a case study. Ultimately, LCCA procedures were employed to determine the cost-effectiveness and viability of the solutions to combat the challenge of sand ingress onto the railway line. In the LCCA process, different options were identified, which include both railway infrastructure design solutions and technical mitigation measures. The LCCA technique results were used as the basis for selecting the best option to mitigate the windblown sand problem on the railway line. Results from this economic analysis presented the humped slab track to be the most cost-effective solution compared to all other options. However, this solution does not prevent the accumulation of sand, especially during sandstorms that frequently blow 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. The study has revealed that in as much as the LCCA method is a good engineering economic tool, it needs to be coupled with viability criterion/criteria to determine the cost-effectiveness of the design and maintenance solutions of this case. It was further noted that the TT system was cost-effective compared to the conventional track system. The analysis concludes that the TT system, which is covered in the tunnel system, is the most feasible and economical solution for addressing the sand problem along the railway line on the dune belt section.

8.2 Recommendations

The following recommendations are proposed from this study:

- The simple deterministic approach used in this study has provided important initial insights into the LCCA results. However, this approach has limitations in terms of analysing input data simultaneously and estimating the likelihood of input values. To improve the accuracy and reliability of future studies, a more powerful probabilistic approach should be utilised, which can incorporate uncertainty and variability into the analysis. Such an approach can build upon the findings of this study and provide a more comprehensive understanding of the subject. Therefore, it is recommended that future studies utilise a probabilistic approach in analysing the LCCA results while recognising the valuable insights provided by the deterministic approach used in this study.
- The unforeseen or indirect costs such as delay costs and environmental costs should be modelled and incorporated into the LCCA to make the estimation of costs more effective. These costs were not simulated in this study, therefore future studies should integrate them into the analysis if there is a cost difference between options.

9. ACKNOWLEDGEMENTS

The author wishes to gratefully acknowledge Dr. P Johannes and Prof. Dr.-Ing. G Bernstein for their good advice, guidance and assistance rendered during this study.

The author also wishes to express gratitude to Mr. Mike Rumsey of Kleber & Associates Consulting Engineers for his valuable contributions and inspiration to pursue this study.

10. REFERENCES

Al-Douri, YK, Tretten, P & Karim, R. 2016. Improvement of railway performance: A study of Swedish railway infrastructure. *Springer,* 24(1):22-37.

Bravenboer, B & Rusch, W. 1999. *The First 100 Years of State Railways in Namibia.* Windhoek: TransNamib Museum.

Bruno, L, et al. 2018b. Shield for sand: An innovative barrier for windblown sand mitigation. *Recent Patents on Engineering,* 12(3):237-246 (10).

Bruno, L, Horvat, M & Raffaele, L. 2018a. Windblown sand along railway infrastructures: A review of challenges and mitigation measures. *Journal of Wind Engineering & Industrial Aerodynamics,* 177:340-365.

Ciszewski, T & Nowakowski, W. 2018. Economic analysis of the life-cycle cost structure for railway traffic control systems. *Ekonomicko-manazerske Spektrum,* 12(1):30-43.

Corbett, IB. 1989. *The sedimentology of diamondiferous deflation deposits within the Sperrgebiet, Namibia,* Cape Town: University of Cape Town .

de Charmoy, CD & Gräbe, H. 2020. Quantifying the economic benefits of gauge changes on the South African core railway network. *The Journal of the South African Institution of Civil Engineering,* 62(3):23-35.

Dierks, K. 2004. *Namibia's Railway System.* Available at:
http://www.klausdierks.com/Namibia_Rail/. Accessed 30 September 2022.

Farran, M & Zayed, T. 2012. New life-cycle costing approach for infrastructure rehabilitation. *Engineering, Construction and Architectural Management,* 19(1):40-60.

Fourie, CJ & Tendayi, TG. 2016. A decision-making framework for effective maintenance management using Life Cycle Costing (LCC) in a rolling stock environment. *South African Journal of Industrial Engineering,* 27(4):142-152.

Galar, D, Sandborn, P & Kumar, U. 2017. *Maintenance costs and life cycle cost analysis.* 1st ed. Boca Raton: CRC Press.

Giunta, M, Bressi, S & D'Angelo, G. 2018. Life cycle cost assessment of bitumen stabilised ballast: A novel maintenance strategy for railway track-bed. *Construction and Building Materials,* 172:751-759.

Grabe, H. 2012. *Tubular track tames the desert,* Pretoria: *International Railway Journal*.

Horvat, M, Bruno, L & Khris, S. 2021. CWE study of wind flow around railways: Effects of embankment and track system on sand sedimentation. *Journal of Wind Engineering & Industrial Aerodynamics,* 208:104476.

Horvat, M, Bruno, L, Khris, S & Raffaele, L. 2020. Aerodynamic shape optimization of barriers for windblown sand mitigation using CFD analysis. *Journal of Wind Engineering and Industrial Aerodynamics,* Volume 197.

Innovation Track System. 2006. *Guideline of LCC and RAMS Analysis.* Paris: s.n.

K&A Consulting Engineers. 2018. *Rehabilitation of the Aus-Lüderitz railway line: Provision of sand shelter tunnel proposal report,* Windhoek: s.n.

Kaewunruen, S, Sresakoolchai, J & Peng, J. 2020. Life cycle cost, energy and carbon assessments of Beijing-Shanghai high-speed railway. *Sustainability,* 12(1):206.

Matos, J, et al. 2018. Life cycle cost, as a tool for decision making on concrete infrastructures. In: DA Hordijk & M Luković, eds. *High tech concrete: Where technology and engineering meet.* Cham: Springer International Publishing AG, pp. 1832-1839.

Mehdipour, R & Baniamerian, Z. 2019. A new approach in reducing sand deposition on railway tracks to improve transportation. *Aeolian Research,* Volume 41.

Patra, AP. 2009. *Maintenance decision support models for railway infrastructure using RAMS & LCC analyses,* Luleå: Luleå University of Technology.

Pichler, W. 2010. *Traffic economics and evaluation of transportation projects: Course manual.* Windhoek: Polytechnic of Namibia.

Raffaele, L & Bruno, L. 2020. Windblown sand mitigation along railway megaprojects: A comparative study. *Structural Engineering International,* 30(3):355-364.

Raffaele, L & Bruno, L. 2019a. Probabilistic assessment of windblown sand accumulation around railways. In: F Ricciardelli & A Avossa, eds. Cham: Springer, p. 562-572.

Raffaele, L & Bruno, L. 2019b. Windblown sand action on civil structures: Definition and probabilistic modelling. *Engineering Structures,* 178(1):88-101.

Rama, D & Andrews, JD. 2016. Railway infrastructure asset management: the whole-system life cost analysis. *The Institute of Engineering and Technology,* 10(1):58-64.

Rießberger, K & Swanepoel, W. 2005. *Specialised sleepers combat sand,* Austria: Railway Gazette International.

Sasidharan, M, Burrow, M & Gurmel, G. 2020. A whole life cycle approach under uncertainty for economically justifiable ballasted railway track maintenance. *Research in Transportation Economics,* Volume 80.

Scheidt, SP. 2013. *Sand transport pathways of dark dunes in the Sperrgebiet: Sand composition and dune migration rates from Aster Data,* Washington: Smithsonian Institution.

U.S. Department of Transportation. 1998. *Life-cycle cost analysis in pavement design: In search of better investment decision.* Washington: Federal Highway Administration.

U.S. Department of Transportation. 2002. *Life-cycle cost analysis primer.* Washington: Office of Asset Management.

Watson, A. 1985. The control of windblown sand and moving dunes: A review of the methods of sand control in deserts, with observations from Saudi Arabia. *Quarterly Journal of Engineering Geology and Hydrogeology,* 18:237-252.

Xin, G, Huang, N, Zhang, J & Dun, H. 2021. Investigations into the design of sand control fences for Gobi buildings. *Aeolian Research,* Volume 49.

Zakeri, JA. 2012. Investigation on railway track maintenance in sandy-dry areas. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance,* 8(2):135-140.

Zakeri, JA, Esmaeili, M & Fathali, M. 2011. Evaluation of humped slab track performance in desert railways. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* 225(6):566-573.

Zhang, Z, et al. 2022. Experimental study and discrete element analysis on lateral resistance of windblown sand railway. *Transportation Geotechnics,* Volume 34.

Zoeteman, A. 2001. Life cycle cost analysis for managing rail infrastructure: Concept of a decision support system for railway design and maintenance. *European Journal of Transport and Infrastructure Research,* 1(4):391-413.

Zoeteman, A. 2003. Life cycle costing applied to railway design and maintenance: creating a dashboard for infrastructure performance planning. *WIT Transactions on The Built Environment,* Volume 64.