To What Extent Does the Railway Network Cover Africa?[1]

Győző A. Szilágyi[2]

Abstract:

The railway network is one of the most important infrastructure elements that connects different regions within a country. The extent to which the railway network is able to make a given area economically and socially accessible affects a country's economic performance and development opportunities. The research examined the spatial coverage properties of the African railway network using chaotic mathematical methods. In this context, the fractal dimension was used as a measure of the planar coverage of linear networks. The research determined the fractal dimension of the entire railway network in Africa, as well as the fractal dimension of those countries that have a significant railway network. The research compared the fractal dimension of the railway networks of the two most significant African countries with a railway network, with those of some European countries. The results obtained quantitatively characterize the railway coverage of individual countries and the African continent as a whole, which allows for a numerical interpretation of the structural differences in the railway infrastructure. The fractal dimension values determined in the research quantitatively reveal the coverage inequalities of individual areas, so they can be used as indicators when determining the priorities of railway network developments.

Keywords:
Africa; Railway Networks; Fractal Dimension; Box-Counting Method.

[1] DOI: 10.12700/jceeas.2026.6.3.524

[2] Senior Lecturer at Óbuda Universitiy, Keleti Károly Faculty of Business And Management, Budapest, Hungary; ORCID: 0000-0002-3294-6760; szilagyi.gyozo@kgk.uni-obuda.hu.

1. Introduction

Africa's railway network constitutes a complex system that goes beyond its mere transport function, and its geopolitical, economic and historical dimensions are crucial in its development. The continent's development path - from colonial conquests in the 19th century to regional integration in the 21st century - is closely linked to the development of its railway infrastructure. The network is highly fragmented, with links between individual countries often lacking and lacking a coherent system in many regions.

There are approximately 75 000 kilometers of usable railway tracks on the continent. (African Union, 2015). By comparison, the United States' rail network is over 250 000 kilometers long, but when you consider the area, the difference is even greater. Africa is roughly three times the size of the United States, yet it has less than a third of the size of the American rail network (Thelo, 2024). Equally important is the highly heterogeneous spatial distribution of the network. Some regions – notably South Africa – operate infrastructure comparable to developed countries, while other states have extremely low rail coverage, and there are countries where there is no rail coverage at all. (Bullock, 2009).

The fragmentation of the network is a direct consequence of Africa's specific history and the logic of colonial economic policy. (Fourie & Herranz-Loncan, 2015). Railway lines built at the turn of the 19th and 20th centuries were typically not geared to local mobility needs or to promoting economic integration between regions but primarily served the extraction of mineral resources and transport to export ports (Kerby, et al. 2017).

The British, French, German, Portuguese and Belgian colonial powers accordingly created an infrastructure network that mainly supported the profit interests and trade policies of the mother countries, rather than strengthening internal relations. A significant part of this structural legacy survived even during the period of independence aspirations starting in the 1960s, and neocolonial economic relations continued to significantly influence the development directions and spatial patterns of the railway network (Jedwab & Moradi, 2016).

2. Research Objectives and Methodology

The main objective of the research is to determine the fractal geometric characteristics of the African railway network and interpret them in a mathematical context. In the research, the fractal dimensional investigation of the spatial structure of the African railway network focused on three topics:

- continent-level analysis, which is an examination of the railway network of Africa as a whole,
- examination of the railway network of the African regions (North, South, East and West Africa),
- examination of the railway network of the two countries with the most developed railway networks (South Africa, Egypt).

- comparison of the obtained results with research results for European countries.

The research used the box-counting method to determine the fractal dimension of railway networks. In the box-counting method, a shape to be examined (in this case the railway network) is covered with an increasingly dense square grid, and the number of covering cells is plotted as a function of different cell sizes. The slope of the function plotted on a log-log scale determines the fractal dimension.

3. The Logic and Effects of Colonialist Railway Development

In order to understand the railway network in Africa, it is essential to understand the goals and considerations that guided railway development during the colonial era. The first African railway line was built in 1856 in Egypt, between Alexandria and Cairo, and the pace of railway construction increased rapidly during the colonial period. However, the development of the railway network did not serve a "civilizing" purpose. The colonial powers – especially the United Kingdom, France, Germany, Portugal and Belgium – mostly created lines that connected the interior of the continent to ports, facilitating the export of mineral raw materials and tropical products (Erdős, 2011).

A well-known example of colonial logic is the idea of the Cape Town-Cairo railway, conceived in 1874 by the British-South African businessman and politician Cecil Rhodes (Weinthal, 1923). Rhodes envisioned a continuous north-south railway axis that would connect the African territories of the British Empire and strengthen Britain's political influence on the continent (Storey, 2025).

The entire project was ultimately not realized, as the economic consequences of World War I, the geographical and political circumstances of the German East African colonies, and later the decolonization process all hindered its completion. However, the railway constructions related to Rhodes – especially in South Africa, Zimbabwe and Zambia – determined the economic relations and raw material-oriented structure of these regions for a long time.

Similar patterns can be observed in other colonial zones. The French administration in West Africa built railways that connected Senegal, Mali, and Guinea, primarily to transport goods from the Gulf of Guinea coast and the wider Lake Chad region (Roberts, 2011). German colonial ambitions also involved the construction of railways in what is now Tanzania, and in the Portuguese colonies – in Angola and Mozambique – export-oriented transport systems organized around ports were established (Meier zu Selhausen, 2025). The Congo Basin became a central arena of colonial competition, and under Belgian rule a railway structure developed that served the needs of copper production (Mavhunga, 2023).

A common feature of these projects is that the railway networks were not adapted to the mobility needs of local societies or to the development of trade between the interior areas of Africa. The lines typically connected the extractive regions with the coastal export ports, and the spatial structure of the network was fundamentally determined by export processes (Gwaindepi, 2019). This asymmetry has led to extreme fragmentation in several places. Even within a country, lines were not connected to each

other, and they often did not fit into the networks of neighboring states at all. (Jedwab & Moradi, 2014)

The fragmentation was further reinforced by the diversity of railway track gauges. In the northern regions of Africa, the 1435 mm (standard) gauge was widespread, in the southern regions the 1067 mm gauge was common, and in Central and West Africa the 1000 mm gauge. In addition, many other variants are present on the continent, and even smaller sections, such as 600 mm and 950 mm gauges, have been created. Such a wide range of gauges and their mixing posed a significant technical and organizational obstacle, and in many cases made continuous cross-border rail transport practically impossible.

4. The Impact of Mineral Extraction and Rail Logistics on the Network

The geographical distribution of mineral resources and their associated transport logistics are key to understanding the spatial structure of the African railway network. The location of mineral deposits, sea and river ports, and economically accessible routes connecting them have all shaped the development of the railway network and continue to strongly influence development directions today. (PPIAF, 2014). After the first diamond deposits were discovered in the Orange River region in 1867, South Africa gradually became a major exporter of gold, diamonds, coal and other valuable minerals. (Janse, 1995). The Democratic Republic of the Congo accounts for 70% of the world's cobalt production (Gulley, 2023), while Zambia and Zimbabwe are famous for their copper mining (Perrings, 1977). In Egypt and Sudan, the development of the railway network was partly adapted to the agricultural production of the Nile Valley and, after the construction of the Aswan Dam, partly to the expansion of energy supply and industrial and transport needs (Bouraima et al., 2023).

The extraction of raw materials is particularly important from a logistical perspective, as deposits are often located far from the coast and major ports. For example, copper from the Katanga region of the Congo and the associated processing facilities required rail corridors that opened up the interior to the Atlantic Ocean. An important element of this was the Benguela Railway to Angola, which was once an important colonial railway network. It connected the port of Lobito with Luau on the eastern border, and also Congo, Angola, Zaire, Zambia, Zimbabwe and Mozambique (Perrings, 1977). It was closed during the Angolan Civil War, but reopened in 2014. Copper from Zambia and Zimbabwe was transported by rail to South Africa, as well as through corridors between British colonies. The spatial configuration of the railway lines was essentially determined by where the transport route between deposits, processing centers, and ports was continuous and could be operated at the lowest cost (Jedwab & Moradi, 2014). The continent's terrain, routes crisscrossed by rainforests and mountains, and the limited capacities of port and related logistics infrastructure in many regions also played a role in this (Naudé & Matthee, 2007).

All this resulted in the development of a single, integrated railway system in many parts of Africa, but rather a collection of relatively separate railway corridors organized

for the export of raw materials (Graff, 2019). As a result, for example, Zambia became dependent on South Africa for its copper exports, and even the TAZARA railway network connecting Tanzania and Zambia, built with Chinese support in the 1970s during the Cold War, was only an indirect solution (Brazinsky, 2024).

5. Development Periods of Africa's Railway Network

The historical development of African railway infrastructure can be divided into four distinct periods (Jedwab & Storeygard, 2017). The first period was the era of colonial expansion between 1850 and 1920, when European powers began to compete intensely for political and economic control over African territories. Following the Anglo-Boer Wars, British influence stabilized, especially in South Africa, while the French sphere of influence expanded its railway development into West Africa, while German colonial structures also consolidated in certain regions of the continent.

The second is the period between 1920 and 1960, when the First and Second World Wars and the intervening global economic crisis slowed down developments due to limited investment capacities and the impossibility of long-term planning. Nevertheless, great power rivalry continued to influence where and in what form railway infrastructure developments were implemented.

In the fourth period, from 1980 to the present, the picture is twofold. In many regions, the condition of railway lines has deteriorated, some sections have become less functional or have disappeared altogether. At the same time, new development programs and financing models have emerged in recent decades, which once again emphasize the strategic role of railways. This trend is reflected, for example, in the increasing participation of China in African railway projects, as well as in the integration-oriented infrastructure development ideas formulated within the framework of the African Union. Such is the case of the AU PIDA program, which aims to modernize and interconnect the network in the longer term (Cokoye et al., 2025). Kenya's "Standard Gauge Railway (SGR)" program, which aims to standardize the country's entire railway network, is also being funded by China (Stölczer et al., 2025).

6. Application of Fractal Dimension in Structural Analysis of Railway Networks

Fractal geometry is a field of mathematics that is specifically suited to describing complex, often self-similar or near-self-similar structures (Mandelbrot, 1977). Mandelbrot's work showed that the geometric properties of many natural and man-made shapes cannot be described satisfactorily by the tools of classical Euclidean geometry but can be well captured by fractal concepts. The spatial patterns of railway networks, such as the system of junctions, branches, main and branch lines, often form such complex fractal structures, therefore the use of the fractal dimension allows for the structural comparability of different railway networks. (Benguigui & Daoud, 1991). Fractal analysis of railway networks is based on the fundamental recognition that these

networks exhibit a hierarchical organization that is repeated at multiple scale levels (Fokasz et al., 1997).

One of the earliest and most fundamental fractal analyses of rail-transport networks was Benguigui's 1995 research on the Paris transport network, which showed that transport networks exhibit characteristic fractal structures (Benguigui, 1995). Batty and Longley's early work on fractal simulation of urban structures also fundamentally influenced this field (Batty & Longley, 1994).

7. Basic Concepts of Fractal Geometry

7.1. Self-Similarity and Scale Invariance

One of Mandelbrot's fundamental insights was that there are many objects in nature and human systems that repeat similar structural patterns at different scales. Classic examples include the contours of coastlines, mountain ranges, the branches and leaves of plants (Mandelbrot, 1977) and the layout of cities or transportation networks. (Helbing et al., 1977). Self-similarity is a fundamental property of fractals, according to which smaller, nested parts of a structure resemble the entire shape, and this similarity can be observed over a wide range of sizes. (Stewart & Golubitsky, 1992). Important geometric features of the system do not “disappear” and do not change significantly when the shape is examined at a different magnification or spatial scale. This idea is particularly relevant in the analysis of railway networks. The organization of the network can in some cases show similar patterns from the level of local line sections to large corridors spanning countries. The hierarchical structure of railway systems – main lines, regional connections, local branches – naturally offers opportunities for the use of the concepts of self-similarity and scale invariance in structural characterization (Fokasz et al., 1997).

7.2. Basic Fractals

The Cantor set is a classic yet easily illustrated example of fractal geometry (Figure 1). Its starting point is the interval [0,1], from which in the first step we remove the middle third of the interval, the interval (1/3, 2/3), as an open interval. In the second step, we do the same for the remaining sections [0,1/3) and (2/3,1]. By repeating this series of steps, we obtain a shape consisting of more and more, but smaller sections. The shapes resulting from each step are similar to the shape obtained in the first step, so the Cantor set is self-similar. By repeating the procedure to infinity, we obtain a shape characterized by the fact that the length of the removed sections is the same as the length of the initial section. Since we have cut open intervals, in the extreme case the length of the Cantor set is zero, but its number of elements is infinite. The initial section has been transformed into a point cloud.

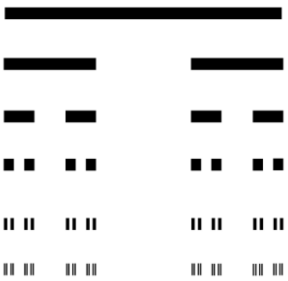


Figure 1: Cantor set (Gyires, 2021).

The Sierpinski carpet is one of the best-known examples of planar fractals (Figure 2). It can be constructed using a simple rule, yet it creates a very complex structure. The starting point of the construction is a unit square, which is divided into a 3×3 grid, and then the middle square is removed. The same operation is then repeated for each of the remaining eight squares. In each subsequent step, the remaining squares are divided into 3×3 parts and the middle square is removed from them. The end result, after an infinite number of iterations, is a shape whose removed area is equal to the area of the starting square, but whose perimeter tends to infinity. The Sierpinski carpet is therefore no longer a plane shape, but has become much more line-type, while maintaining its self-similarity.

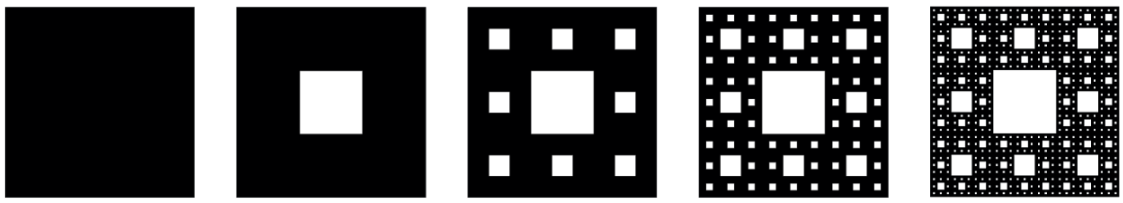


Figure 2: Sierpinski carpet (Kuznetsova et al., 2025).

Like the Cantor set, the Koch curve starts with a straight-line segment (Figure 3). This segment is divided into three equal parts, the middle third is removed, and two new segments are inserted in its place, creating an equilateral triangular bulge. The same step is repeated for each of the remaining four segments, and then the process is repeated infinitely. The Koch curve is also self-similar. At each step, a segment is replaced by four segments reduced to 1/3 of its original length. The length of the Koch curve thus increases with each iteration, up to infinity, while the entire curve remains within a limited range.

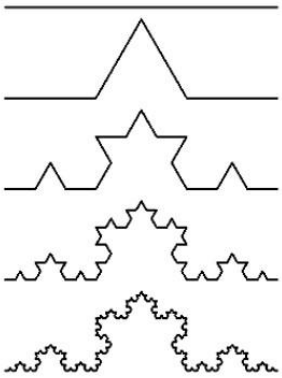


Figure 3: Koch curve (Purnomo et al., 2019).

The Peano curve is a space-filling type of shape that also starts from a straight-line segment. In the first step, we divide the segment into three equal parts, then we fit a square at the top and bottom of the middle segment. In the next step, we replace the two squares with a continuous line that traverses all edges of the squares and connects the two original 1/3-length segments (Figure 4). The Peano curve has the property that although it starts as a line, it can cover a larger and larger part of the plane with infinite iterations. The length of the Peano curve increases exponentially with each iteration, and eventually goes to infinity, while the shape itself remains in a bounded, square domain. The Peano curve is topologically one-dimensional, but in terms of its space-filling ability, it behaves like a two-dimensional object.

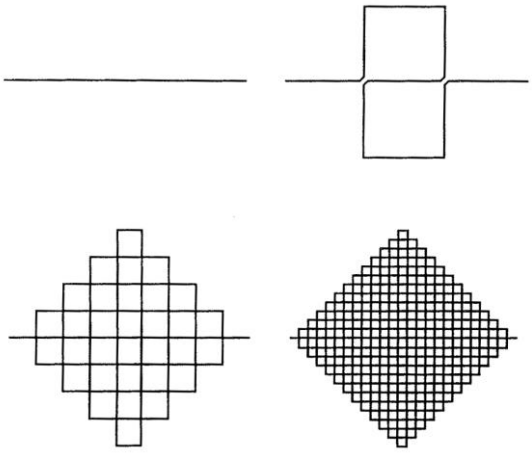


Figure 4: Peano curve (Bovill, 1996).

7.3. The Fractal Dimension

In spatial dimensions, a point has zero dimensions, a line or plane curve has one dimension, a plane figure has two dimensions, and a solid has three dimensions. The number of spatial dimensions reflects the topological structure of the object. However, we can also test the one-dimensional nature of a curve by seeing how it can be covered

with smaller and smaller sections. We find that the smaller sections we cover of the curve under consideration, the larger the value we get for its length, and even if we use a measuring device of the same accuracy, the measured result still depends on where we start measuring on the curve. This is the so-called shoreline problem. (Richardson, 1961). Figure 5 shows that although the curve of the coastline of Great Britain is the same in all cases, we still get different results when using measuring instruments of different accuracy.

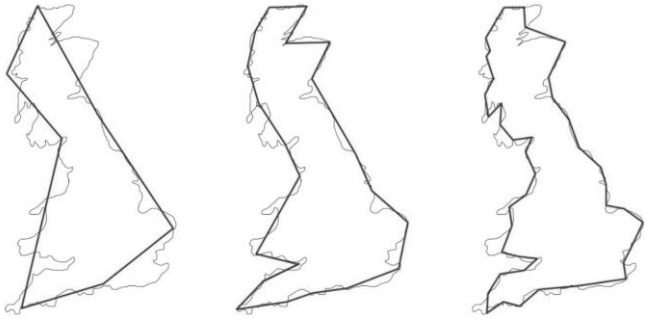


Figure 5: The shoreline problem (Mandelbrot, 1977).

Fractal dimension is a generalized geometric measure that characterizes how a shape or network "fills" space at different scales. In the classical approach to Euclidean geometry, dimension is an integer for different shapes. However, in the case of fractals, dimension is often not an integer, but rather expresses the extent to which the object can fill space. For example, a Koch curve is more than a simple line, but less than a complete plane surface. Fractal dimension is a quantitative measure of geometric complexity. The larger the fractal dimension of a shape, the more structurally complex the shape is. (Skums & Bunimovich, 2020).

7.4. Box-Counting Dimension

When we want to determine the fractal dimension of an irregular plane figure, the similarity dimension method is often not applicable, since irregular shapes are not constructed in such a way that the entire shape is self-similar. In such situations, box counting is one of the most commonly used methods for numerically estimating the fractal dimension. In the box-counting method, a square grid is placed over the shape under consideration, and then the cell size is gradually reduced, and at each step we count how many cells have a point in common with a point on the shape. For example, if we initially use a 10×20 grid and then reduce the cell size by half, the number of cells needed to cover the 20×40 grid increases but typically does not double. The rate of increase depends on the “complexity” of the shape. As the cell size becomes smaller, a typically power-law relationship develops between the number of cells required for coverage and the cell size:

$$N_r \propto r^{-D_b}$$

where N_r is the number of cells that have a point in common with the shape, r is the cell size, and D_b is the box-counting dimension. Therefore, the box-counting dimension:

$$D_b = \frac{\log N_r}{\log(1/r)}.$$

The method is applicable not only to regular, deterministic fractals, but also to general planar shapes. Due to the nature of the method, randomization does not change the fractal dimension, and the box-counting method can be widely used to estimate the fractal dimension of any planar shape (Benguigui & Daoud, 1991).

8. Applicability of Fractal Analysis to the Analysis of Railway Networks

In the case of fractal analysis of railway networks, the box-counting method is easy to apply and allows for the rapid analysis of large networks. The map of the railway network must be covered with a grid, and then the number of cells covering the network must be assigned to each cell size by continuously reducing the cell size. The values are displayed on a logarithmic scale, and the slope of the line that best fits the points gives the value of the fractal dimension. The fractal dimension is an indicator that can be used in practice because it expresses how efficiently the railway lines fill the geographical area under study (Batty & Longley, 1994).

The application of fractal analysis to the study of railway networks has several advantages. It allows the measurement of complex morphology, as the fractal dimension expresses the topological complexity of the network in the form of a single number, which allows for objective comparison. Due to the scale-independent nature of the box-counting method, networks of different sizes and organization can be compared. If individual temporal changes are documented, the change in fractal dimension can be used to examine how the railway network reflects infrastructural and geopolitical priorities (Cai et al., 2023). Fractal analysis can also be used to verify whether rail network developments produce structures that correspond to real, known fractal values. However, the application of fractal analysis has several limitations that must be taken into account. The value of the box-counting dimension depends on the chosen grid sizes and the scale range examined. Distortion can occur if the analysis is performed on a scale that is too large or too small. In practice, it is recommended to use a grid size reduced in 5–10 steps. In line with this, we halved the grid size in 8 steps in the research.

Railway networks are not natural systems, but the result of human decisions that take into account the location of economic resources and political considerations. It should therefore be noted that fractal analysis does not explain these causal factors but only makes the structural complexity of different networks measurable and comparable.

Data quality issues also affect the results. The accuracy of digital maps, incomplete or outdated data, and topological variations can all affect the results of fractal analysis. If we want to compare the fractal dimension of different railway networks, we need to use maps with the same scale. It is also important that the line thickness representing the

railway lines on the maps is the same, because the line thickness also sets a limit to the reduction of the grid size (Szilágyi, 2025).

9. Material and Methodes

To examine the railway network, we used the online, interactive map of OpenRailwayMap (OpenRailwayMap, 2025), which is part of the OpenStreetMap (OSM) community database. OpenRailwayMap contains detailed data on the railway networks of all countries, and the interactive map displays the following information for each railway line:

- railway infrastructures and their identifiers (e.g. bridge, tunnel, stations, etc.),
- speed limits,
- type of railway signaling system,
- operating voltage values of electrified lines,
- gauge width.

The map displays elements with the same properties in the same color, which also facilitates visual identification. The map is zoomable and provides a kilometer and mile scale at the current zoom level. It refines the geometry of the route as you zoom in, while displaying it with a constant line thickness. These features are particularly useful for using the box counting method when using a large, high-resolution display.

The study was conducted separately for several territorial units. For each territorial unit, an image crop with the same scale and display settings was used to make the results comparable. We performed a fractal analysis of the railway network of the following territorial units:

- the entire territory of Africa,
- regionally divided into North Africa, East Africa, South Africa, West Africa,
- and two countries, Egypt and the Republic of South Africa.

Since the railway network of the African continent is very rare not only compared to other continents, but also in itself (Figure 6). The railway network of most African countries consists of only a few railway lines, so the continental railway network does not form a continuous, complex network. Only the two countries under study have a railway network for which fractal geometry analysis makes sense.

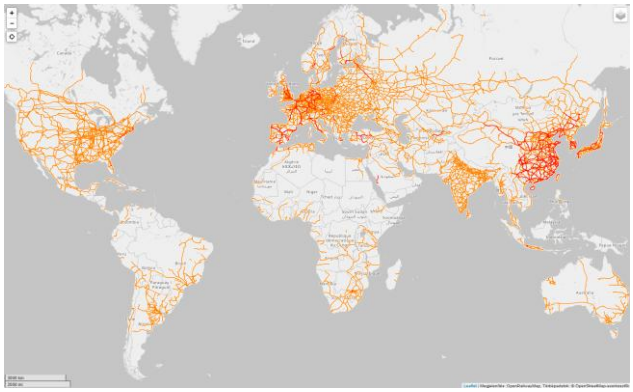


Figure 6: The railway map of the Earth (OpenRailwayMap, 2025).

For the analysis, we used the FrakOut software, which uses a box-counting method to determine the fractal dimension of the given shapes. In order to increase the accuracy, the relevant cells were selected not with a mouse, but with an XP-pen Deco 01 V3 digital drawing tablet. This tool allowed us to continuously select the relevant cells in the image, not by clicking one by one, but by dragging the associated pressure-sensitive digital pen along the line. The software applies a square grid to the map crop, on which the cells that have a common point with the examined shape, in this case the given railway network, have to be selected. Then, we increased the grid density using the software, thus reducing the cell size, and repeated the identification of affected cells with the smaller cell size.

The software counted the number of cells that have a common point with the examined shape at each step, and as a result of the iteration steps, it calculated the fractal dimension of the examined shape. In the research, we reduced the cell size in eight steps, which is consistent with the empirical value of research conducted using the box-counting method. The individual cell sizes r and their corresponding box numbers used in the analysis were plotted on a log-log diagram, and a straight line was fitted to them using linear regression. According to the box-counting method, the slope a of this straight line gives the fractal dimension D_b :

$$N(r) \propto r^{-D_b} \quad \Rightarrow \quad \log N(r) = a \log r + b, \quad D_b = -a.$$

9.1. Interpretation of Fractal Dimension in a Railway Context

The fractal dimension of the railway network is closely related to the spatial complexity, flexibility and economic organization of the network. D_b values close to 1.0 can be interpreted as a linear, one-dimensional network with a single, not excessively winding railway line. In such a network, there is usually only one possible route between two points, its capacity is low, and its vulnerability is high. Such a network is very sensitive; if an error occurs, its transmission capacity is significantly reduced or may even be zero. A value of D_b around 1.5 indicates a slight complexity, but the network's space-filling capacity is still low. In such a network, points can be reached via several possible routes, and due to the possible detours, its disturbance tolerance is higher, but even small disturbances affect its capacity. A value of D_b above 1.8 indicates high complexity and area-filling characteristics, which are typical of dense, highly branched networks that cover a larger area. These networks have high fault tolerance and are able to maintain their capacity within certain limits even in the event of faults. (Cai et al., 2023).

10. Research Results

10.1. The Fractal Dimension of Africa's Entire Railway Network

Based on the map of the African railway network, it was already visually likely that the analysis would yield a low fractal dimension for the continent as a whole, which was confirmed by the results of the box-counting analysis. The map clearly shows that the railway coverage of some regions of the continent is asymmetrical (Figure 7).

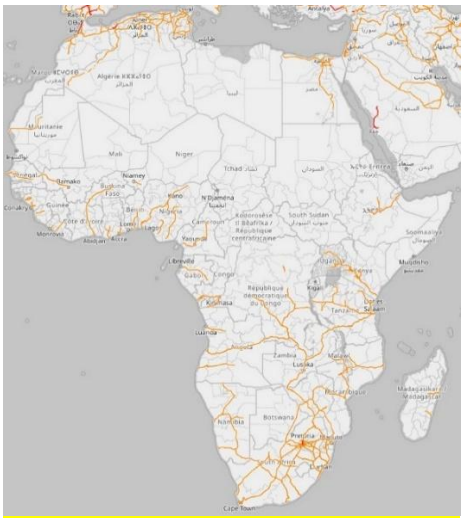


Figure 7: Africa's railway network (OpenRailwayMap, 2025).

The railway network of most African countries is characterized by the fact that it consists of main lines and branch lines connecting to them, and these local lines correspond to tree-graph type that are not connected to each other. There are only two regions where the railway network is not tree-graph type, and each main and branch line form a complex network that is also connected to each other. One of these is the Southern African region, and within it, typically the Republic of South Africa, and the other is the railway network of the areas near the Mediterranean Sea in the North African region. Figure 8 shows the results of the analysis for the entire continent of Africa, performed using the box-counting method, in a log-log diagram.

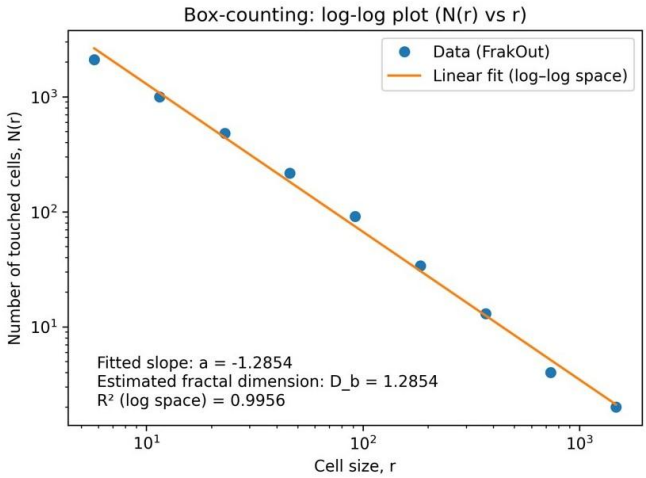


Figure 8: Africa's $D_b^{AFR} \approx 1.2854$; $R^2 \approx 0.9956$ (Own figure).

The resulting fractal dimension is significantly lower than, for example, the fractal dimension of the European railway network $D_b^{EUR} \approx 1.74$ (Fokasz et al., 1997), but no conclusions should be drawn from this alone. The population density of a given continent must be taken into account, as rail transport develops between populated and

industrial areas. The African continent has large areas of uninhabited land due to climatic conditions, while in the case of Europe the proportion of uninhabited land is small.

10.2. The Fractal Dimension of the North African Railway Network

The coastal regions of North Africa, in the northern parts of Egypt, Morocco and Tunisia, have relatively well-developed railway networks, but Algeria, apart from a short section, has almost no railway network. Figure 9-12 shows the results of the fractal geometry analysis of the region. The low fractal dimension value ($D_b^{NAFR} \approx 1.1208$) is also influenced by the fact that the railway lines are located in a more densely populated zone close to the Mediterranean coast, while there are no railway lines in the Saharan areas. The West African region also includes a significant amount of sparsely populated land, and therefore the fractal dimension of the region is also strongly influenced by regional borders defined based on political and economic considerations. The fact that the fractal dimension of East Africa ($D_b^{EAFR} \approx 1.2568$) is higher than that of West Africa ($D_b^{WAFR} \approx 1.2179$) may also be a consequence of this effect, but a causal verification of this is beyond the scope of this research. Although in the case of South Africa ($D_b^{SAFR} \approx 1.4164$), in addition to the colonial effect, the geometric shape of the continent also plays a role in the high fractal dimension value. Despite all these effects, since the research followed regional boundaries determined based on economic and political considerations, the fractal dimension can be considered an economically relevant indicator for strategic decisions in railway developments.

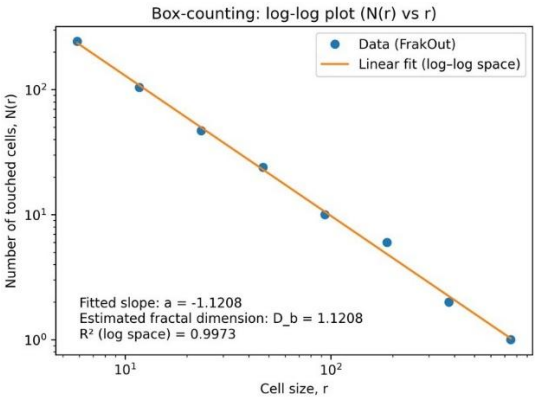


Figure 9: North Africa's $D_b^{NAFR} \approx 1.1208$; $R^2 \approx 0.9973$ (Own figure).

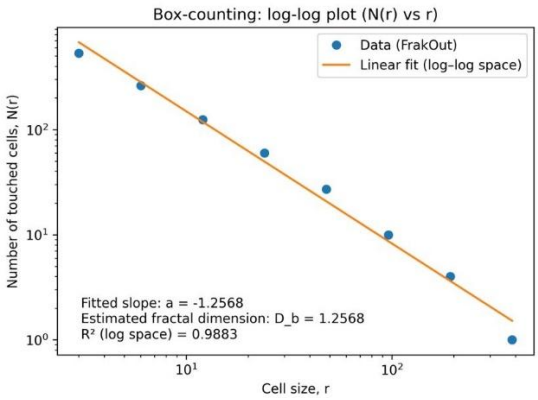


Figure 10: East Africa's $D_b^{EAFR} \approx 1.2568$; $R^2 \approx 0.9883$ (Own figure).

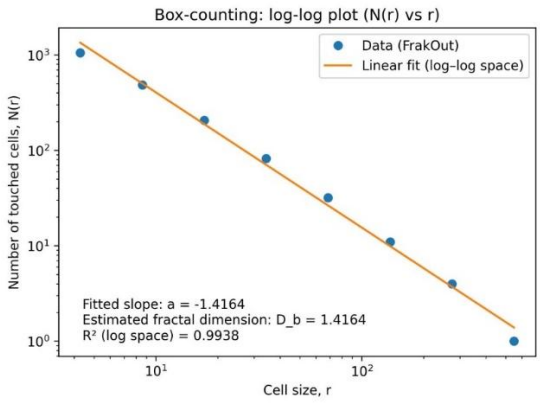


Figure 11: South Africa's $D_b^{SAFR} \approx 1.4164$; $R^2 \approx 0.9938$ (Own figure).

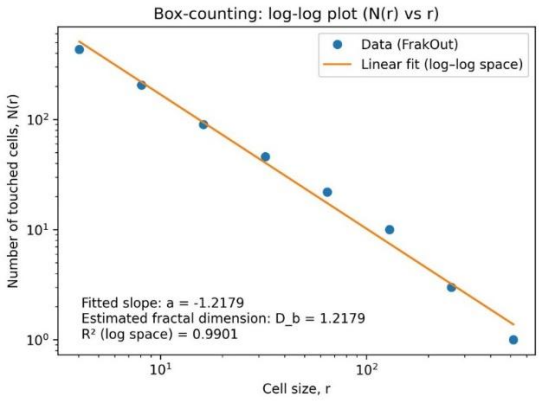


Figure 12: West Africa's $D_b^{WAFR} \approx 1.2179$; $R^2 \approx 0.9901$ (Own figure).

10.3. Fractal Dimension of the Railway Network of Egypt and the Republic of South Africa

The two African countries with the most complex railway networks are Egypt and the Republic of South Africa. The results of the fractal analysis of these two countries are shown in Figures 13 and 14. Although the fractal dimension of Egypt is lower than that of the Republic of South Africa, using the results of Fokasz et al. (1997), we find that Egypt, with its $D_b^{EGY} \approx 1{,}2994$ is ahead of Turkey ($D_b^{TUR} \approx 1{,}18$) and Greece ($D_b^{GRE} \approx 1{,}24$).

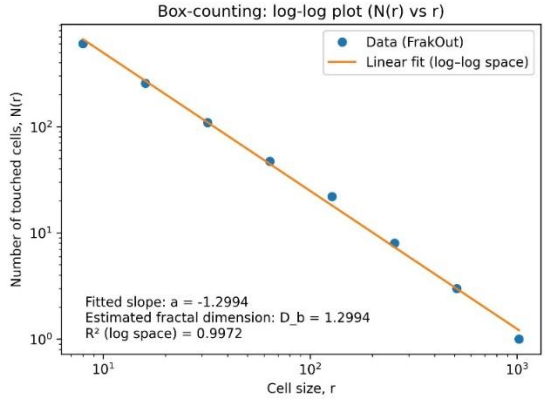


Figure 13: Egypt's $D_b^{EGY} \approx 1.2994$; $R^2 \approx 0.9972$ (Own figure).

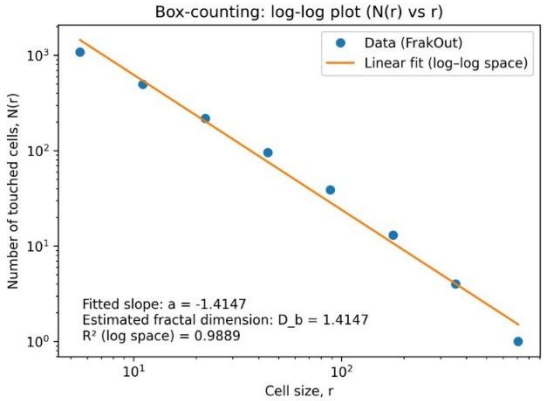


Figure 14: Republic of South Africa's $D_b^{SAR} \approx 1.4147$; $R^2 \approx 0.989$ (Own figure).

South Africa is the best-covered African country with a railway network. Its fractal dimension ($D_b^{SAR} \approx 1{,}4147$) is close to that of Italy ($D_b^{ITA} \approx 1{,}48$), but still significantly lags behind the values of European countries such as Great Britain ($D_b^{GBR} \approx 1{,}68$), Germany ($D_b^{GER} \approx 1{,}78$), France ($D_b^{FRA} \approx 1{,}76$) (Fokasz, Kopper, Maródi, & Szedenics, 1997). An interesting result is that the country's tail dimension is almost exactly the same as the value obtained for the Southern African region. This is probably due to the country covering a significant area of the region.

11. Summary

This study examined the spatial coverage and structural characteristics of the African railway network using fractal geometry methods and demonstrated how historical periods influenced the development of the railway network on the continent. The research aimed to quantitatively determine the spatial coverage of the network of the continent, its regions, and the two most advanced countries in terms of railways. The methodological basis of the research was the box-counting procedure, which allowed the quantification of the spatial coverage of the network using the fractal dimension. The analysis used the OpenRailwayMap digital database and FrakOut software, and a digital drawing board for the box-count procedure to ensure accuracy. The results highlighted the extremely low level of coverage of Africa's railway network. The value obtained for the entire African continent's fractal dimension is far below the Europe's value, reflecting the low level of area coverage of the network. The regional analysis also revealed significant infrastructural inequalities. The highest complexity was shown by the Southern African region and the Republic of South Africa's value, where the network density is already approaching the level of some Mediterranean European countries. In contrast, in North Africa the network is concentrated in the coastal area, while in West Africa the fragmented, tree-graph type structure dominates. Low values indicate a lack of real connectivity in most regions. The research findings can inform the African Union's integration programs in railway development strategies, helping to prioritize development and promote economic connectivity at the continental level.

Conflict of Interest

The authors hereby declare that they have no financial interest in this manuscript.

Notes on Contributor

Győző A. Szilágyi Ph.D. received his doctorate in military engineering from Doctoral School on Security and Safety of Óbuda University, and his research field is the operational safety of complex systems. In his research, he examines the operational security aspects of complex technical and human networks using network science and chaotic mathematical methods. He is an senior lecturer at Óbuda University.

References

African Union. (2015). *African Union.* Towards The African Integrated High Speed Railway Network (AIHSRN) Development: Retrieved December 10, 2025 from https://au.int/sites/default/files/documents/32186-doc-towards_the_african_integrated_high_speed_railway_network_aihsrn_development-e.pdf

Batty, M., Longley, P. (1994). *Fractal Cities: A Geometry of From and Function.* San Diego: Academic. https://doi.org/10.5555/179240

Benguigui, L. (1995). A Fractal Analysis of the Public Transportation System of Paris. *Environmental Planning A*, 27(7), pp. 1147-1161. https://doi.org/10.1068/a271147

Benguigui, L., Daoud, M. (1991). Is the Suburban Railway System a Fractal? *Geografical Analysis, Vol.23*, pp. 362-368. https://doi.org/10.1111/j.1538-4632.1991.tb00245.x

Bouraima, M., Alimo, P., Agyeman, S., Sumo, P., Lartey-Young, G., Echebrecht, D., Qui, Y. (2023). Africa's railway renaissance and sustainability: Current knowledge, challenges, and prospects. *Journal of Transport Geography, Vol. 106,*, pp. 1-12. https://doi.org/10.1016/j.jtrangeo.2022.103487

Bovill, C. (1996). *Fractal Geometry in Architecture and Design.* Boston: Birkhauser.

Brazinsky, G. (2024). *US-China Rivalry in Asia and Africa: Lessons from the Cold War, No. 530, 2024 June.* Wahington: Unites States Institute of Peace.

Bullock, R. (2009). *Off Track: Sub-Saharan African Railways.* Washington: The World Bank.

Cai, X., Chen, S., Lian, X. (2023). Study on the structural characteristics of China's high-speed railway network and its coordination with economic growth based on Fractal theory, Vol. 9, Issue 11. *Heliyon*, pp. 1-22. https://doi.org/10.1016/j.heliyon.2023.e22321

Cokoye, C., Osegbue, C., Okelue, C., & Emesieni, I. (2025). Assessing the Impact of Programme for Infrastructure Development on Intra-African Trade Growth (2013-2023). *International Journal of Humanities Social Science and Management, Vol. 5, Issue 2*, pp. 1059-1068.

Erdős, F. (2011). *Afrika Közlekedése.* Pécs: Publikon Kiadó.

Fokasz, N., Kopper, Á., Maródi, M., Szedenics, G. (1997). Az európai nemzeti és regionális vasúthálózatok fraktáljellegéről. In Á. Horváth, *Rend és káosz* (old.: pp. 257-268.). Budapest, Replika Kör.

Fourie, J., Herranz-Loncan, A. (2015). *Growth (and Segregation) by Rail: How the Railways Shaped Colonial South Africa, No. 538.* South Africa: Economic Research Southern Africa (ERSA).

Graff, T. (2019). *Spatial Inefficiencies Afrika's Trade Network.* Cambridge, National Bureau of EconomicmResearch.

Gulley, A. (2023). China, the Democratic Republic of the Congo, and artisanal cobalt mining from 2000 through 2020. *PNAS, Vol. 120, No. 26*, pp. 1-11. https://doi.org/10.1073/pnas.2212037120

Gwaindepi, A. (2019). *Serving God and Mammon: "Mineral-Railway Complex" and Its Effects on Colonial Public Finances in The British Cape Colony, 1810-1910.* Sweden, The African Economic History Network, Lund University.

Gyires, B. (2021). *Gyires Béla Tananyagtár.* Retrieved December 10, 2025 from https://gyires.inf.unideb.hu/KMITT/b24/ch03s03.html

Helbing, D., Keltsch, J., Molnár, P. (1977). Modelling the Evolution of Human Trail Systems. *Nature Vol. 388, No. 3*, pp. 47-50. https://doi.org/10.1038/40353

Janse, A. (1995). A History of Diamond Sources in Africa: Part I. *Gems & Gemology, Winter 1995, Vol. 31, No. 4*, pp. 228-255.

Jedwab, R., Moradi, A. (2014). Transportation Technology and Economic Change: The Impact of Colonial Railroads on City Growth in Africa. *Institute for International Economic Policy Working Paper Series*, pp. 1-64.

Jedwab, R., Moradi, A. (2016). The Permanent Effects of Transportation Revolutions in Poor Countries: Evidence from Africa. *Review of Economics and Statistics*, pp. 268-284.

Jedwab, R., Storeygard, A. (2017). *Economic and Political Factors in Infrastructure Investment: Evidence from Railroads and Roads in Africa 1960–2015.* Washington, Institute for International Economic Policy Working Paper Series, George Washington University.

Kerby, E., Moradi, A., Jedwab, R. (2017). *CEPR.* How colonial railroads defined Africa's economic geography: Retrieved February 10, 202 from https://cepr.org/voxeu/columns/how-colonial-railroads-defined-africas-economic-geography

Kuznetsova, S., Allein, F., Dal Poggetto, V. F., Bécot, F.-X., Miniaci, M. (2025 No. 25,). Sierpiński carpet-inspired hierarchical patterning of porous materials for sound absorption. *NPJ Acoustic*, pp. 1-11. 10.1038/s44384-025-00023-8.

Mandelbrot, B. (1977). *The Fractal Geometry of Nature.* New York: Freeman and Co.

Mavhunga, C. (2023). Africa's move from raw material exports toward mineral value addition: Historical background and implications. *MRP Bulletin*, 1-13. https://doi.org/10.1557/s43577-023-00534-3

Meier zu Selhausen, F. (2025). *German Colonialism in Africa and the Pacific, 1884-1914.* Utrecht, Utrecht University, African Economic History Working Paper, No. 80.

Naudé, W., Matthee, M. (2007). *The Significance of Transport.* Helsinki: Inited Nations University.

OpenRailwayMap. (2025). *OpenRailwayMap.* OpenRailwayMap: Retrieved December 10, 2025 from https://openrailwaymap.org/

Perrings, C. (1977). Good Lawyers but Poor Workers': Recruited Angolan Labour in the Copper Mines of Katanga, 1917-1921. *Journal of African History*, *18*(2), 237-259. https://doi.org/10.1017/S0021853700015516

PPIAF. (2014). *Fostering the Development of Greenfield Mining-Related Transport Infrastructure Through Project Financing.* Washington: World Bank Publications.

Purnomo, K., Sari, N., Ubaidillah, F., Agustin, I. (2019). The construction of the Koch curve (n,c) using L-system. *International Conference on Science and Applied Science (ICSAS).*

Richardson, L. (1961). The problem of contiguity: An appendix to Statistics of Deadly Quarrels. *General Systems: Yearbook of the Society for the Advancement of General Systems Theory, 6*(139), pp. 139-187.

Roberts, T. (2011). Republicanism, Railway Imperialism, and The French Empire in Africa, 1879-1889. *The HIstorical Journal, Vol. 54, No. 2*, pp. 401-420. https://doi.org/10.1017/S0018246X1100070X.

Skums, P., & Bunimovich, L. (2020). Graph fractal dimension and the structure of fractal networks. *Journal of Complex Networks*, 1-24. https://doi.org/10.1093/comnet/cnaa037

Stewart, I., Golubitsky, M. (1992). *Fearful Symmetry. Is God a Geometer?* Oxford: Blackwell.

Storey, K. W. (2025). *The Colonialist: The Vision of Cecil Rhodes.* Fairford, United Kingdom: Oxford University Press.

Stölczer, K., Szádeczky, T., & Besenyő, J. (2025). Africa's Energy Transition: Challenges, Opportunities, and Geopolitical Dimensions. *Journal of Central and Eastern European African Studies*, *5*(1), 21-35. https://doi.org/10.12700/jceeas.2025.5.1.343

Szilágyi, G. A. (2025). Fractal Dimension of the Railway Networks of Hungarian Counties. *INDECS*(22(3)), pp. 272-283. https://doi.org/10.7906/indecs.23.3.7

Thelo. (2024). *Tackling Africa's rail infrastructure deficit.* thelo: Retrieved December 10, 2025 from https://thelo.africa/media/tackling-africas-rail-infrastructure-deficit/

Weinthal, L. (1923). *The Story of the Cape to Cairo Railway and River Route from 1887-1922.* London: The Pioneer Publishing Companv.