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Exploring Aswan's Transportation Network through Graph Theory: Metrics and Insights.

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Abstract

Graph theory is crucial for efficient route planning; networks facilitate movement, transportation, communication, and control over matter and energy. This research introduces an overview of graph theory and its basics. The paper illustrates the different types of graphs and their important metrics (such as centrality degree, betweenness degree, and the accessibility degree). These metrics provide insights into connectivity flow and network efficiency, enabling the identification of critical nodes and routes. The provided methodology consists of two parts: the first part is about converting the topographic network to a graph (nodes and links), and the other part is about metrics calculations. Aswan city issued as a case study and all relevant data are displayed. The paper starts with the Aswan scenario graph, and then measures the metrics for all points showing weakness and the strength nodes of the graph. The finding showed an integrated picture of the Aswan road network, explaining the characteristics of each node. The results are considered a benchmark for understanding the nature of Aswan and a useful tool for decision-makers.

Keywords: Public Transportation; Graph theory; Graph metrics; transportation network

1. Introduction

Cities are rapidly evolving and expanding. As the population grows, so does the demands for more and diverse types of housing, employment opportunities, and access to services, which results in a growth in modes of transportation and the number of cars on the roads. Economic, social, and environmental development all depend heavily on transportation. The goal of transportation and mobility is to move people and things as effectively as possible while having the fewest detrimental effects on society and the environment; therefore, it is important to improve, understand, and analyze road networks. One of the important steps to understand networks is to convert them into a graph, as the graph is the foundation on which network analysis and representation depend.

This research presents in a simplified manner the steps for converting the road network from the topographic network to the simplified graph, taking the city of Aswan as a case study. The research does not stop at converting the network and representing it but rather delves into measuring some indicators and measurements in the network that help to understand the nature of the network and understand its characteristics adequately. This research paper consists of several sections, starting with the introduction, then the second section is an overview of the graph theory, then section 3 is about previous studies related to the topic, and the scientific methodology comes in section 4, then the results are presented and discussed in section 5 and ends with the conclusion of the topic.

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2. Literature Review

Networks were initially employed to solve mathematical problems; graph theory has been presented as a solution to the Königsberg bridge problem [1]. They wondered if it was possible to go across a city and across each bridge precisely once. Similar research [2], asked if a knight could visit every square on a chessboard exactly once. In order to count specific types of hydrocarbon molecules, [3] investigated structures resembling networks. The mathematical discipline of graph theory emerged as a result of these studies. What we refer to in this paper as networks and what mathematicians more often call graphs are interchangeable definitions. In engineering and optimization, the term "network" is more frequently used [4].

Many previous studies have dealt with the theory of graphs in the field of transportation and roads. Some of them used the theory in road design and planning, and some of them used it in improving road networks. For example, [5] proposed a framework for studying the causative processes of waterway transport accidents employing Interpretive Structural Modeling (ISM) and graph theory. This technique used graph theory to improve traditional network analysis by giving a thorough representation of the accident causation network and emphasizing the complicated relationships between multiple causative elements. Chen et al. [6] outlined a knowledge graph-based solution to digital contact tracking in public transit during the Corona Virus Disease 2019 (COVID-19) epidemic, emphasizing its superiority over existing techniques. It described the creation of a knowledge graph using smart card and transit data. Their results showed high accuracy in forecasting public transportation transactions and exhibiting a large reduction in infection risk using a modified Wells-Riley model. The study emphasized the benefits of knowledge graphs for integrating multi-source data, improving contact tracing efficiency, and modeling epidemic spread, while also recognized the limitations and the need for additional research in dynamic virus transmission and public health policy impacts. Kalaivani et al. [7] explored the challenges and uses of graph analysis, particularly in real-time contexts, emphasizing themes like complexity, scalability, data quality, standards, and privacy concerns. They investigated several ways for analyzing directed graphs and solving transportation issues based on game theory and graph theory principles, including conventional strategies such as the North-West Corner Rule and novel approaches such as the multipartite graph method.

Some studies have focused on transit systems: Liu et al. [8], graph theory was used to analyze and simulate transit networks, with transit stops or stations represented by nodes and route segments linking them represented by connections or edges, each with features such as trip time and cost. This research used graph theory tools to assess the global efficiency of Toronto's transportation network, focusing on the impact of service disruptions on disadvantaged users vs. the general population. Furthermore, the study presented a time-expanded graph technique, which allows for more accurate trip time predictions by taking real-time data and the impacts. Hu et al. [9] utilized graph theory to create a trip-based subway travel network, with nodes representing entrance and exit stations and edges representing travels between these stations. The study uses complex network theory to extract dynamic indicators and characteristics for forecasting passenger flow. The Graph Convolutional Network (GCN) model is also cited as a way to manage non-Euclidean data by aggregating information from surrounding nodes in a graph structure. Song et al. [10] used graph theory approaches to assess the overall efficiency of Toronto's transportation network, focusing on the impact of service disruptions on disadvantaged users vs. the general population. Additionally, the study proposed a time-expanded graph technique, which allows for more accurate journey time predictions by taking into account real-time data and the implications of headway performance.

From these studies, we conclude the importance of having a graph and its various uses, For the knowledge of the author there are no studies that explain the graph measurements as an application to a Aswan network case study. Therefore, this study presents a graph metrics and insights for Aswan network.

2.1 Basic Definition

A graph is made up of a collection of items known as nodes and certain pairs of these nodes connected by links known as edges as shown in figure 1 [11]. The nodes are called "vertices" in some investigations. A single symbol, such as a letter or number, designates a network node, which might be an intersection, a bus or rail station, a factory, a warehouse, a store, an airport, or a port. Although they are connected to each other by edges, not all of them have to be; any two nodes could have more than one edge linking them. If two nodes are connected by an edge, we refer to them as neighbors. Edges that link the nodes together have several names that are the same, such as arcs, lines, vertex pairs, and links. Take note that each link's notation includes the two nodes it connects. The link's head refers to the downstream node and the tail to the upstream node [4]. Depending on the kind of network, the edges can represent a variety of physical meanings, as shown in the following table (Table 1).

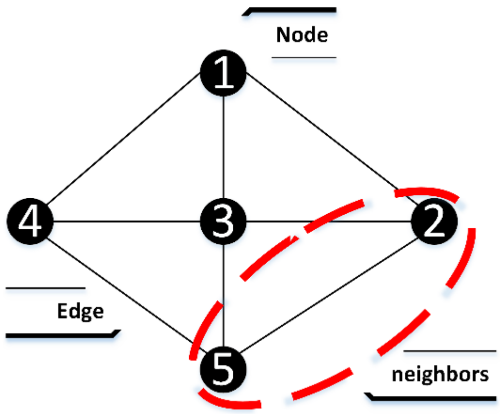

Figure 1 Representation of Simple Graph.

Table 1 Different Types of Edges According to the Type of Network.

Network Type	Edges
Roadway	segments of streets
Commuter transit	Route segments
Air	Flights
Maritime	Shipping channels
Freight	freight options

2.2 Graph Types

There are numerous graph kinds that fall into several categories as illustrated in figure 2, all of which are distinguished from one to another by their unique design. Since a graph may incorporate many classifications, it becomes more adaptable and relevant in multiple contexts. They are enumerated as follows [12].

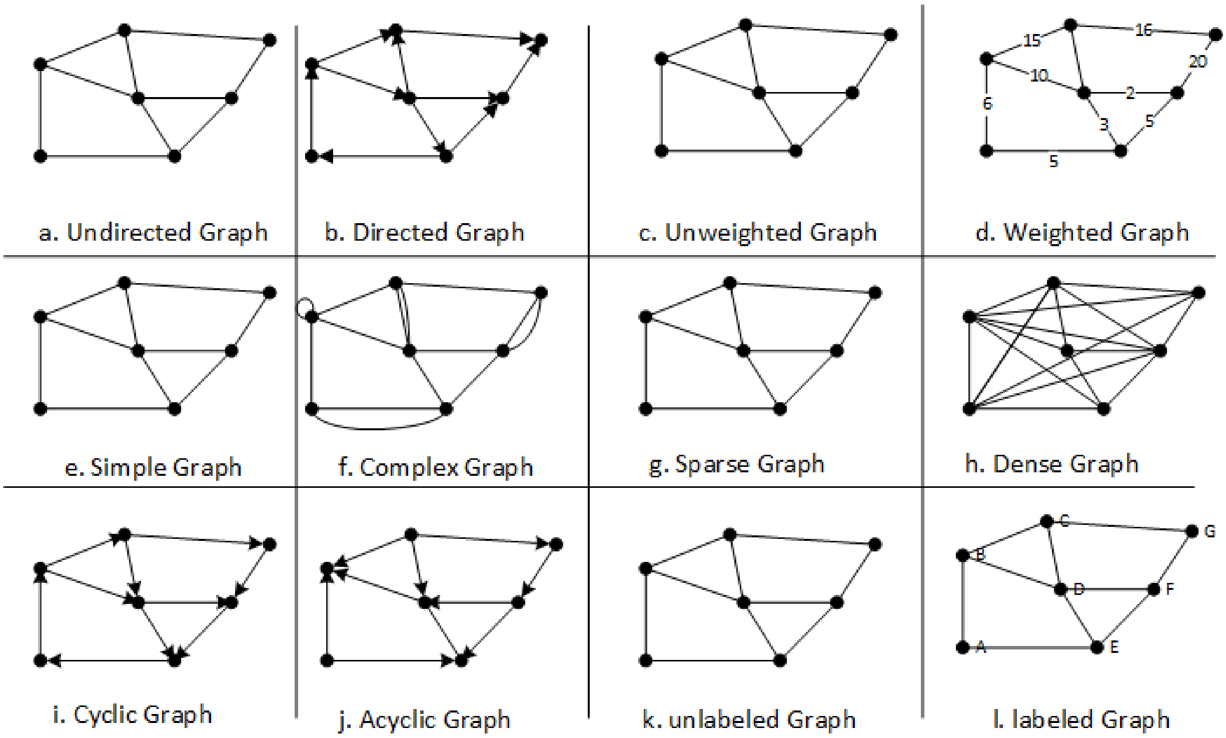

Figure 2 Different Graph Categories.

It is separated into six categories, with two opposing types in each category:

- Directed Graphs: are also called digraphs, a graph in which all the edges are directed.
- Undirected Graphs: There is no direction on the edges.
- Weighted Graphs: A numerical value, or weight, is assigned to each edge (or vertex).
- Unweighted Graphs: There is no difference in value between different vertices and edges.
- Simple Graphs: A graph having no self-loops and no parallel edges.
- Complex Graphs: at least contain one or more self-loops, which means two edges with the same pairs of edges.
- Sparse Graphs and Dense Graphs: When few feasible pairs of vertices have edges established between them, the resulting graphs are said to be sparse. Dense graphs are ones in which most pairs of vertices define edges. Although the distinction between dense and sparse graphs is not clearly defined, dense graphs usually have quadratic numbers of edges, whereas sparse graphs have linear sizes. Because of road intersections, road networks need to be sparse graphs.
- Cyclic Graphs: Any graph with at least one cycle, and vice versa Acyclic Graphs.

- Labeled Graphs: It is given a special name or identifier in order to differentiate it from every other vertex.
- Unlabeled Graphs: all vertices without names or symbols.

There are many special cases in which graphs exist and may carry one or more of the previous classifications, which can be listed as follows:

- Pseudo Graph: are graphs with self-loop(s) but no parallel edges.
- Euler Graph: A connected graph where every vertex has an even degree.
- Hamiltonian Graph: If a closed walk exists in the linked network that visits each vertex precisely once, omitting the starting vertex, and doesn't repeat edges.

3. Material and Methods

3.1. Graph Modeling

As mentioned before, the graph (G) consists of edges (E) and nodes (N) and edges' weights (W). With respect to nodes, it represents the start and the end of streets, the intersection of streets, and any change of the street characteristics, and for edges, it reflects the streets or links, and the time factor will be used as the edge weight.

ArcGIS is among the greatest planning programs available. So the edition 10.8 is used to getting the network using UTM (Universal Transverse Mercator) with projected coordinate system WGS (world geodetic system) 84 / UTM zone 36 N.

Road Google Maps Server was integrated with the road file created for the study region by the Egyptian Military Survey Authority, as shown in figure 3. The resulted urban network has a large amount of data that includes all types of roads (roadways, footways, etc.), road characteristics (travelling speed, direction, name, etc.), and parking areas. All unnecessary roads, side roads, and roads unsuitable for automobile use are eliminated, and then the base network is made.

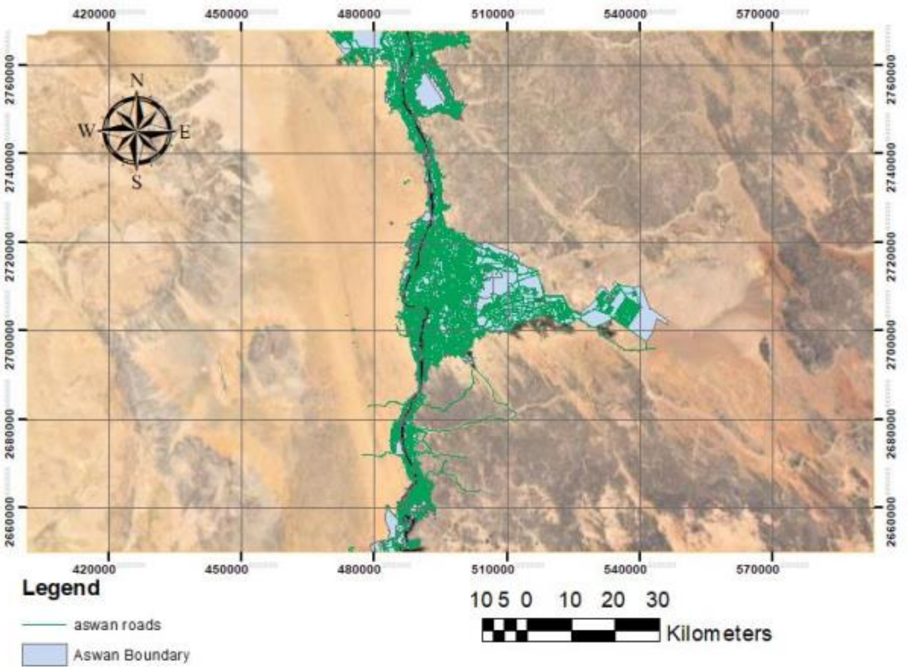

Figure 3 Base Aswan Map

The map is converted from ArcGIS to AutoCAD. Initially the nodes are defined as previously outlined, and after that, the length of each link between two nodes is determined.

Travel time through routes is used for each link, and this time is calculated using travelling speed for vehicles, which is dependent on the classification of the road as illustrated in the Egyptian Code for Urban and Rural Roads. Building the graph and all calculations is done using MATLAB programming. A device with Intel(R) Core(TM) i3-3217U CPU @ 1.80GHz is used to solve the model.

3.2. Metrics Calculations

There are different metrics to understand the structure and behavior of graphs. Among them are centrality, betweenness, average path length, density, connectivity and accessibility.

These metrics are quantitative measures used to identify the properties of graphs and understanding the relationships between nodes and edges [13].

3.2.1. Degree Centrality

Degree centrality refers to the total number of connections, interactions, edges, or links a node has [14]. And its importance for identifying critical intersections or hubs with high connectivity and high-degree nodes often indicates busy junctions or transfer points [15].

$$\boldsymbol{C_{D,i} = N_{E,i}} \quad (1)$$

Where,

- $C_{D,i}$ is the degree of centrality of node (i).
- $N_{E,i}$ is the number of edges is connected to a node (i).

3.2.2. Betweenness Centrality

The percentage of shortest paths that cross through a particular node of interest is known as betweenness centrality, and this indicator is important, so the nodes with high betweenness have a very heavy traffic load.

$$\boldsymbol{C_{B,i} = \sum \frac{N_{P,(s,t)}(i)}{N_{P(s,t)}}} \quad (2)$$

Where,

- $C_{B,i}$ is the degree of betweenness centrality of node (i).
- $N_{P(s,t)}$ is the number of shortest paths from node (s), and node (t).
- $N_{P(s,t)}$ (i) is the number of those paths passing through node (i)

3.2.3. Accessibility

It helps to measure how reachable a node is within a network and is important in transportation planning because it helps identify well-connected locations, optimize routes, and improve access to underserved places. They promote equity in urban design by ensuring that everyone has access to important services such as schools, hospitals, and marketplaces.

$$\boldsymbol{A(i) = \frac{1}{n-1} \sum d(i,j)} \quad (3)$$

Where,

- A(i) is the accessibility of node (i).
- d(i,j) is the shortest path distance between node (i), and node (j).
- n is the total number of nodes in the graph.

4. Experimental Results and Case Study

Based on the graph shown in figure 4 for the Aswan city, the network consists of 40 nodes and 55 edges, and this makes the network as a medium-sized network, and the network can be categorized as a simple, acyclic, sparse, labeled, and weighted graph.

According to the directness category, the road network as a whole may be a directed graph or an undirected graph, but for the Aswan network type, it should be a directed graph because it has single-way roads. To take the advantage of two-way roads and single-way roads in any analysis operations at the same time, the mirrored network technique is used, which is illustrated in [16].

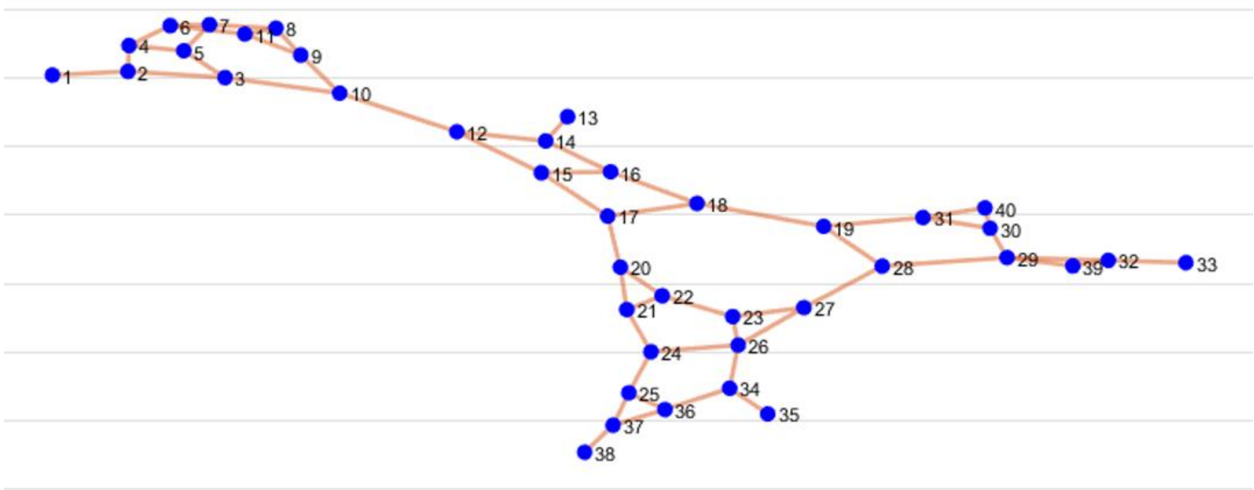

Figure 4 Aswan City Graph (nodes and links)

4.1. Aswan Metrics (Degree Centrality)

The degree of centrality is a nodal metric for which the mean is calculated for each node, and the degree is illustrated in figure 5. The results show that there are three groups of points: the first group of 4 degrees consists of nodes (27 and 29), and the second group, which scores the least degree of centrality, consists of nodes (1, 13, 33, 35, and 38) with a value of 1, and the other nodes form the last group with 3 degrees of centrality. This leads to the first group containing the largest number of potential conflict points, which means that these nodes are a priority for decision-makers in traffic planning and providing them with control devices.

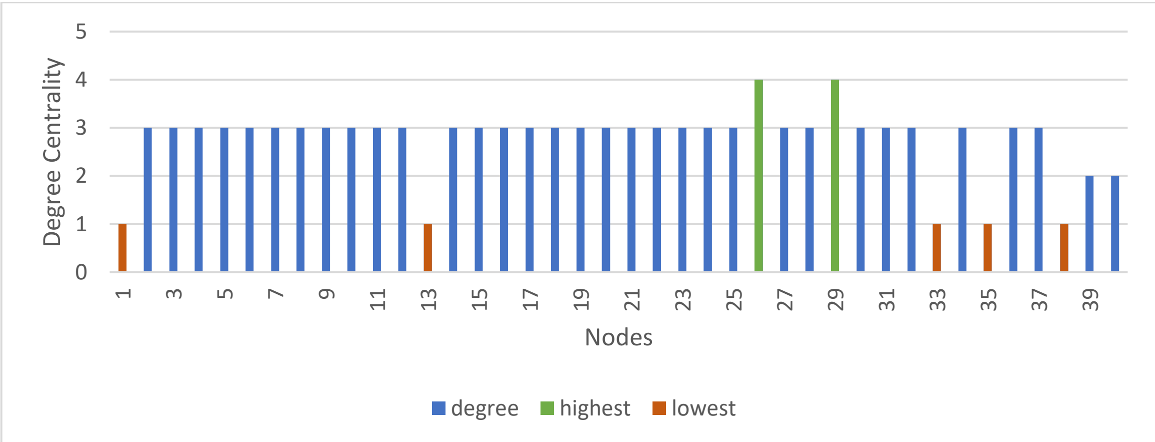

Figure 5 Degree Centrality for Aswan Network.

4.2. Aswan Metrics (Betweenness Centrality)

According to betweenness centrality degree, as shown in figure 6, the results show a big change in values, with node 12 scoring the maximum degree with a value of 300, and other nodes not having a betweenness degree, which means that there is not any shortest path passing through these nodes. As for node 12, which has the highest value in this indicator, this means that it has a weight in the bottleneck analysis, which indicates its importance in facilitating the flow of traffic. Therefore, any damage to this node will negatively affect the entire network, and therefore it is important for it to be at the forefront of priorities in terms of development, improvement, and monitoring by officials.

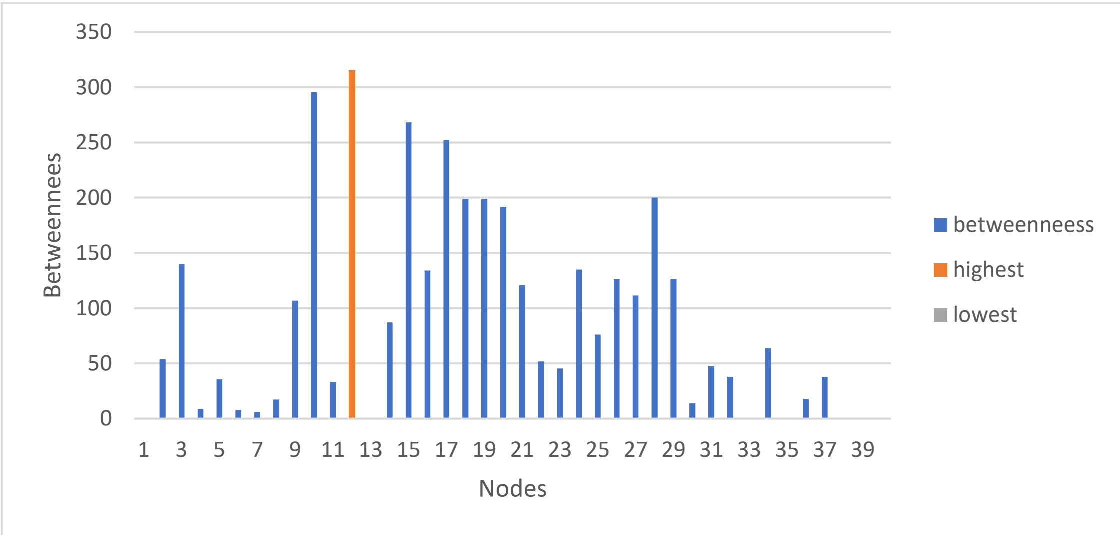

Figure 6 Betweennees Degree for Aswan Network.

4.3. Aswan Metrics (Accessibility)

The results for the accessibility are illustrated in figure 7, and the results show variation in the accessibility values of different network nodes.

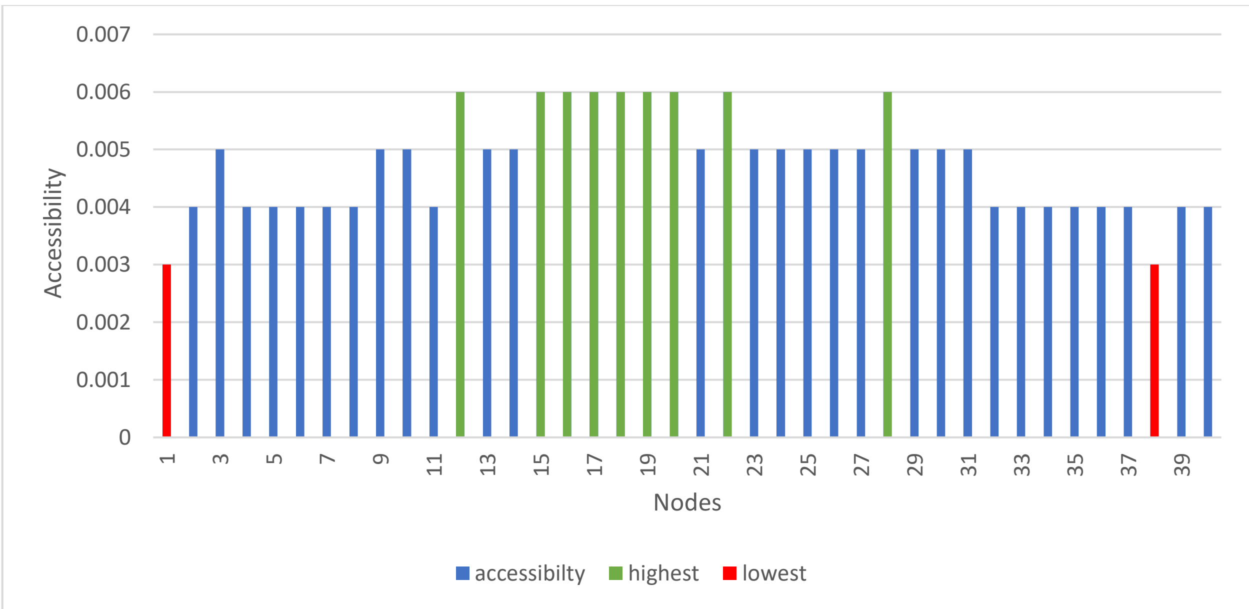

Figure 7 Accessibility Indicator Score for Aswan Network

The points (12, 15-20, 22, and 28) score the highest accessibility nodes, and this indicates the centrality of these nodes, their weight, and their strong connection with other places, which facilitates the movement of individuals. Due to the importance of these areas, they can act as a service center for people, as they can be easily accessed from the rest of the areas in the network. But here is an important note regarding the node with the lowest value for accessibility, which is node 1, which is the closest place to the high-speed train station, which is the national project in Aswan. In order for the project not to be negatively affected, accessibility must be increased in any way, such as establishing public transportation lines and others. But it is noted that most of the points are equal in the index, which means that all areas are available in terms of access to them, which creates an integrated and equal network in equality.

5. Conclusion

This research offered a study on graph theory, detailing its types, graph components, multiple uses, and the criteria on which the network is assessed and compared, and its features are defined, using Aswan as a case study because it has never been researched previously.

After obtaining the Aswan network as a preliminary result in the form of nodes and edges, the measures of accessibility, centrality, and betweenness were looked at, explaining their values for all points and critical points in each measure. These values should be among the design priorities and serve as a starting point for future research.

And it is also concluded that the point of the high-speed train station with the lowest value in the accessibility index, one of the most critical points, and this problem must be solved in order for the project to succeed.

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