Masters Program in **Geospatial Technologies**

ROBUSTNESS OF ROAD NETWORK FOR ASSESSING THE RESILIENCE OF THE NETWORK

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ROBUSTNESS OF ROAD NETWORK FOR ASSESSING THE RESILIENCE OF THE NETWORK

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Declaration

I hereby certify that this thesis, entitled “Robustness of the road network for assessing the resilience of the network”, has been entirely composed by me and is based on my own work and under the guidance of my supervisors. Data collected by me is genuine and was used exclusively in this thesis. No other person’s work has been used without due acknowledgment. All the references used have been cited, and all sources of information, including graphs, illustrations and data sets, have been specifically acknowledged.

Signature

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Robustness of road network for assessing the resilience of the network

ABSTRACT

Road network infrastructures are important public assets that play crucial services in economic development like trade and community services like emergency services. The absence of road network connectivity by flooding, accident, strategic terrorist attack and traffic jam critically and strongly affects the operation of the entire road network [1]. Using a representative three km radius OSM sample data of Addis Abeba's city road network and by measuring the giant component size and diameter change caused by both strategic and random node removal, we assessed the robustness of the network. By simultaneously analyzing the robustness result with global efficiency measure, as an availability measure of the route, we finally assessed the resilience of the network. Our result shows that from giant component size measure, the road network was robust from randomly removing 24% *pc* value of nodes than strategically removing 4% *pc* value of nodes. The diameter measure increases from 39 to 51 paths and from 39 to 43 paths against random and strategic node removal respectively. From diameter measure, we conclude that a decreasing diameter measure in response to BC based strategic node removal does not always show a robust network. Rather, the physical structural connectivity determines the robustness measure. In conclusion, greater than 88% of the network was vulnerable for both strategic and random node removal and were not able to be robust and resilient as well. Thus, this finding gives an ample understanding of the cities road network robustness and resilience. Therefore, city planners and administrators can infer about the need of the cities road networks re-design and expansion activities. Additionally, this study helps them to see the city road network's vulnerability against betweenness centrality based strategic attack than randomly attacking the road network and this later helps to identify points of BC measures.

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KEYWORDS

Robustness

Resilience

Percolation

Strategic node removal

Random node removal

Road network

Open street map

Centrality measure

Giant component giant component size

ACRONYMS

OSM - open street map

OSMnx – open street map and networkx

BC – Betweenness centrality

nx - networkx

1. INTRODUCTION

Road infrastructures are important public assets that play crucial services in economic development like trade and community services like emergency services. The absence of road network connectivity, rapid urbanization, increased motorization and population number, and poor public transport system is challenges of this infrastructure. Of these, road network connectivity is critical and strongly affects the operation (use) of the entire road infrastructure [1]. Urban planners and administrators thrive to maintain and assure those crucial services specifically transport and movement of people, goods, and ambulance and police services.

The increasing motorization level and absence of well-connected road network challenge the availability of those services within the city. However, increasing road infrastructure level in terms of its size and strength against disturbances like flooding, traffic jam, accident, and terrorist attacks helps to achieve the goal of having an adequate and a well-connected road network. The presence of such a well-connected road network facilitates a successful delivery of the above-mentioned services.

A well-connected road network is composed of an integral node and edge components. Removal of those components either randomly or strategically [2] from the road network leads to a disconnection or collapse of the entire network[3]. Road network robustness, an important property of a network, is the ability of a network to withstand the removal of such components i.e. nodes and edges ([2], [4]and [5]).

Over the last few decades, a large number of methods was developed within the network science community to study road network robustness([5], [6] and [4]). Since city road networks have a high probability of exposer to any of those disturbances, it is difficult to generalize the cities road network robustness only from either strategic or random node removal perspectives. Thus, exposing a road network to both random and strategic node removal techniques helps to better assess and make a better generalization about the road networks robustness property [7].

Road network resilience, the other important property of the road network, also helps to measure the persistence of the network and its ability to absorb disturbance and preserve the connectivity[8]. There are too much misunderstanding and unclear definition and applications between robustness and resilience [9]. According to the definition of robustness, it measures the general strength of the network against the removal of its components. Whereas, resilience not only measures the strength of the network but it also measures the availability of any route, in our case road route, between points within the network after the network loses its robustness.

Originally, a network has one robustness property measure at one point in time, independent of the node removal technique, and it changes over time in response to node removal. Thus, those property measures i.e. robustness and resilience of a road network behave differently against the application of random and strategic node removal techniques. This leads us to the conclusion of robustness and resilience measure being different for different node removal techniques.

In order to change the road network from connected to the disconnected network, some critical amount of node should be removed from the network by applying a strategic or random node removal technique [2]. This breakage point (amount of node removed) is called the critical percolation probability pc [10]. Both road network robustness and resilience measures use this pc point to assess the robustness and resilience of the network. We will now rethink those measures and demonstrate our method to assess the resilience of the network from robustness measure by removing nodes using both strategic and random node removal techniques.

In this study, it was of interest to assess the road networks resilience from its robustness measure while applying both strategic and random node removal techniques. To achieve this goal, we measure and compare the networks diameter and giant component size for both strategic and random node removal techniques. Additionally, to assess the resilience of the road network, we developed a novel methodology by simultaneously analyzing global efficiency and robustness measures i.e. diameter and giant component size into one integrated double axis line graphs.

In particular, to achieve the research goals this study analyzes the following research questions:

- What is the critical point of node removal to lose its connectivity?
- What is robustness of the road network against node removal?
- What is the resilience of the road network based on robustness measure?
- Which node removal technique results for a more robust and resilient road network?

To achieve those goals and objectives while addressing the above-mentioned research questions, we used a sample road network that can be a very good input for the study. Addis Abeba's city road network data, which suffered from flooding, traffic congestion, and motor vehicle accidents, was downloaded from OSM and pre-processed for the study. Additionally, as far as we know, there no previous research has investigated those questions and the robustness and resilience of the city's road network. From this study, the main achievements, including contributions to the network science community, would be to give a general robustness and resilience impression of the cities road network, Addis Ababa.

2. RELATED WORK

In this chapter, we present a brief review of existing works in the context of road network robustness and resilience assessment from defining and conceptualizing network robustness and resilience in selecting centrality metrics. This chapter also presents two percolation methods (strategic node removal and failure) as a part of robustness and resilience assessment as well as post percolation measurements like diameter and giant component measures. The first section presents the road network structure and then the second section discusses road network robustness and resilience. The final sub-section presents centrality measures used for robustness and resilience assessment.

2.1. Road network structure

The term network refers to the assembly of routes between nodes as a system of locations and route is a single link between two nodes([11] and [12]). The connection and arrangement of a network are represented by a graph G = {V, E}, where V is a collection of nodes connected by edge E with the direction([13] and [14]). However, networks with two adjacent and opposite one-directional edges are undirected networks.

Measuring network properties like degree distribution P(k), k is a degree, (***Figure 2.1***) helps to understand network structure [12]. Such a measurement of networks property enables us to categorize a network as random e.g. road network, small-world and scale-free networks e.g. airline network[11]. Random networks [15] has a typical Poisson degree distribution property- a homogenous connectivity distribution property of the network - with a high average value and decline exponentially (***Figure 2.1 a***).

A significant recent discovery, small world network, by [16] is a new form of network. Small-world networks are characterized with a sufficient slow mean short distance increment between nodes as the number of nodes in the network increases. The concept of a small world network was, in fact, important to show the topological proximity of distant nodes [17].

Remarkable recent research in the field of complex networks like the Internet, metabolic networks and road network is the statement of scale-free networks. Scale-free networks have a power-law form of connectivity distributions i.e. connectivity distribution increases as a node are added to the network ([16], [18], [12] and [19]) (***Figure 2.1 b***).

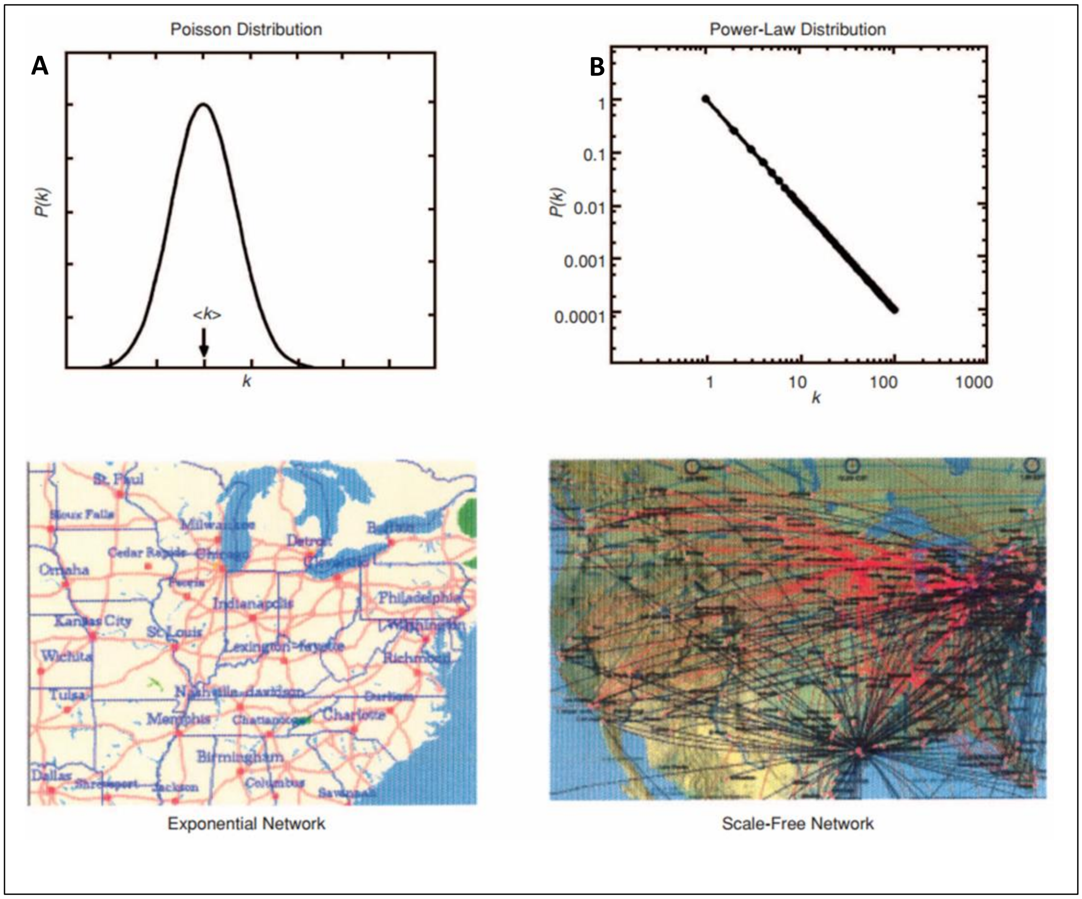


Figure 2.1 *(Adopted from [19]): Differences between a Random node removal or exponential network—a U.S. roadmap and a scale-free network—an airline routing map*

Measuring the structure of the network using its connectivity helps to understand the topologic and geometric variation of the network structure [13].

In terms of road networks, the irregularity of such structures mostly comes from the construction of the road in a different period of time[11]. Additionally, a limited road capacity, vast investment to build long distance roads and a high cost of each link to be attached to a given node are a couple of other reasons that make road network structure irregular [19].

The presence of those reasons about irregular road network structure does not make urban roads are homogenous. Homogeneous road networks nodes have almost the same number of edge connections. Small-world and random network exhibit such behavior and show a peaking average value connectivity distribution behavior and this distribution decays exponentially (***Figure 2.1 a***) [12]. But, the presence of a differentiated operation like highways, tunnels and functional properties like Collectors, arterials rather makes urban road networks heterogeneous [13].

2.2. Centrality measure

A node located in the center of a network is assumed to be more central than any other nodes [20]. However, the question of how to identify this central node from other nodes within the network becomes an ambiguity for such centrality concept. Every node within the network has positional information [21] like a number of edges connected to a node and distance from another node. [21] used such positional information's of a node to tackle those ambiguities in identifying a specific central node.

According to [21], It was able to come up with three different positional information categories possessed by the central node. Those central node positional information categories are:

- A central node can be a node with maximum possible *degree* i.e. a number of connected edges to the central node.
- A central node can be a node located *between* the largest possible numbers of other points within the shortest path and
- A central node can be a node located *close* to another node with a minimum distance.

Thus, based on the above three central nodes positional information category, [21] introduced degree, betweenness and closeness centrality measures respectively to the network science community.

Betweenness centrality was originally proposed by [22] ***equation (1)*** which were later implemented in networkx by [23] as.

$$\mathrm{CB}(V) = \sum_{s,t \in V} \frac{\sigma(s,t|v)}{\sigma(s,t)} \qquad \text{Equation (1)}$$

Where V is the set of nodes, σ(s,t)) is the number of shortest paths between node *s* and *t*, and σ(s,t|v) is the number of those paths passing through some node v other than s,t. In this case, If s=t, σ(s,t)=1, and if v∈s,t, σ(s,t|v)=0 [23].

Generally, betweenness centrality measures the other nodes dependence on a given node, and therefore it is a potential controller measure [24]. A related measure to betweenness centrality i.e. closeness centrality which measures the average length of the shortest path between a node and all other nodes ([24] and [20]).

There is a hot debate about the correlation between centrality measures. [25] examined that both closeness and degree centrality measures are highly correlated. [25] also argue that all centrality measures have different mathematical equations, refer to [26] and [22] equations, and this results in different centrality measurement values.

Most importantly, centrality measures help to identify influential and significant nodes within a network. Depending on the type of network like road, social, internet and epidemic network significant nodes have different interpretations for different networks. For example, a significant road network node helps to connect nodes using edges and removing this node makes the network to lose its connectivity. On the other hand, a significant node in a disease outbreak network will have a different meaning, which is vaccinating a host person, a significant node, will stop the transmission of disease.

A great number of authors have discussed the application of centrality measure in assessing the robustness i.e. strength of the road network against node removal. For example, research by [27] and [28] applies Betweenness, Closeness, Degree, and Eigenvector centrality measures to investigate the robustness of the road network. Over time, an extensive literature has shown the applicability of centrality measure to assess the robustness of a network against node removal ([27],[29],[30] and [22]). Those studies affirm that betweenness centrality measure is a common centrality measure used to study networks property like robustness [25].

However, addressing questions regarding the high computation time for computing betweenness centrality measure raises an enormous concern. A previous study ([24]and [31]) shows the need for high computation time to calculate betweenness centrality. [32] acknowledged and addressed this problem using his new street network-analyzing toolkit, OSMnx. According to Boeing, this toolkit is a computationally efficient tool to compute network statistics like betweenness centrality.

2.3. Percolation

The interconnection between the network's component i.e. nodes and edges determines the function of networks. The removal of some of those components from the network raises questions regarding the network's connection and function in general [3]. The nature of node removal i.e. random and strategic determines the robustness of the network. In a random node removal, each node in the network is removed with the same probability [2] and a strategic node removal depends on the centrality measure types of the network [27] (***discussed in section 2.2***). As a result, the removal of a critical amount of nodes either strategically or randomly changes the network from connected to the disconnected network and this phenomenon is addressed using percolation theory [2].

Many researchers demonstrate numerous efforts to examine the network's connectivity by removing nodes either randomly or strategically ([33], [34], [2] and [10]). From those studies, after a continuous node removal, there is some critical point where a network changes from connected to the disconnected network in response to the node removal and this point is called critical percolation probability pc [10]. This critical point helps to determine or answer the question of network robustness and resilience. Therefore, the conclusion of road networks robustness and resilience comes from the consideration of pc.

2.4. Road network Robustness and Resilience

Road networks exposure to unforeseen hazards like incidents, traffic jams and floods is getting a growing awareness [35]. Robustness and resilience assessment against such an incident helps to measure the road networks strength.

2.4.1. Road network robustness

The presence of a connected road network determines the success of economic development like trade and social activities (e.g., working, recreation, freight, etc.). However, the performance of such a connected road network is also challenged by incidents like traffic congestion, terrorist attack, flooding, and a car accident [34]. The insensitiveness of the road network to such an incident is assessed using the robustness measure of the road network [35]. According to [35], "robustness is the extent to which, under pre-specified circumstances, a network is able to maintain the function for which it was originally designed”. This approach helps assures the availability of a connected network by considering the extent to which the network can tolerate those pre-specified circumstances or disturbance. The author also suggests that, since those pre-specified circumstances are hard to set, policymakers are required to make a pre-specified circumstance or disturbance choices.

Most recent studies focus on robustness assessment of road networks using single disturbance, which is without considering concurrent incidents like a terrorist attack, flooding, or car accidents. A study by [36] in Hong Kong examines the robustness of a road network with multiple incidents and found out as a quite different and complete measure than single disturbance measure. On another study by [2], it was possible to examine the robustness of the network after removing influential and random node removal nodes.

The networks change from such node removal (strategic and random node removal) can be recorded using the network's properties like the giant component size – a growing network component size in proportion to the number of nodes - and diameter of the network. [29] applied the giant component size measure to study the robustness of the network against all possible strategic node removals of the undirected networks. Because of this approach, calculating the giant component size during all network random and strategic attack is simple and practical for robustness measure [5].

Network diameter is also one of robustness assessments measure. Most of the time, robust networks are characterized by a small diameter measure [37]. Indeed, a small diameter certainly points toward all the nodes are in the vicinity and the network is compact [30]. However, a smaller increment of network diameter upon nodes removal also makes the network robust [38]. A few low-degrees with high-load and highly connected nodes of the network are properties of this measure [5] have also advocated the use of robustness assessment using diameter measure to promote bus network design.

2.4.2. Road network resilience

A closer look into the concept and definition of resilience articulates a number of disparities. There are more than 25 definitions of resilience from different study perspectives (e.g., road, biology, internet) [9]. In this section of the thesis, we discussed some of the leading thoughts of resilience that is significant for this work.

The pioneering concept of resilience by [8] from an ecological point of view measures the persistence of a system and absorbance of disturbance and thus maintains the populations' relationship. Holling's work focused on the measurement of the continuity of the system by measuring the resistance and absorbance of disturbances. [4] also measure the resilience of the road network by measuring the recovery time from such a disturbance. The resilience measurement using Calvert and Snelder method was possible to measure the recovery time of the road network from traffic congestion. Additionally, natural systems as protein-protein-interaction (PPI) networks are prominent examples to show such an ability to retain its functions back from failures and strategic node removals [39]. An immense misperception and misunderstood of resilience comes from [35] work and [35] presented resilience as one element of robustness.

Resilience was also abstracted by [40] in disaster management study and was able to see resilience from a reduced probability of failure of the network, reduced recovery time and minimal negative consequence. This approach involves measuring the resiliency level of the network before losing tolerance from disturbance[41]. [40] also show that resilience can be measured using recovery time from failure. Thus, the [40] considered a network with reduced recovery time, reduced result of failure and less chance of the work for failure as a resilient network.

Road network resilience was also examined by [42] as road networks ability to adopt adaptive and transformative approaches to give the needed service while the network is under disturbance [43]. In this article, the author considers the adaptive and transformative approaches for resisting strategic node removals to facilitate the network routine services.

A leading and sturdy argument of resilience in road network comes from the [44] work which [27] later use the concept to evaluate network robustness. The most accepted and leading [44] work on the structure and function of a network highlights the networks function dependence on connectivity or the existence of paths between nodes. Removing nodes from a network increases the length of the path between nodes and this creates a less resilient network. This approach was helpful to examine the resilience of the network for such node removal [45].

[46] examine the robustness and resilience of the network with time. The author presents the assumption that a network will be robust for a short period but becomes fragile and will not guarantee the long-term resilience of the network. From this, the robustness and resilience of a network are two different measures.

3. METHODOLOGY AND TOOLS

3.1. Introduction

This section of the thesis outlines the study methods used to conduct the research (***Figure 2***). The researcher describes the tools used and how the required data collected, processed and analyzed to address the research questions and objectives. Reasons and justifications about data acquisition and pre-processing, network analysis, centrality measure, percolation, robustness, and resilience assessment techniques used are given.

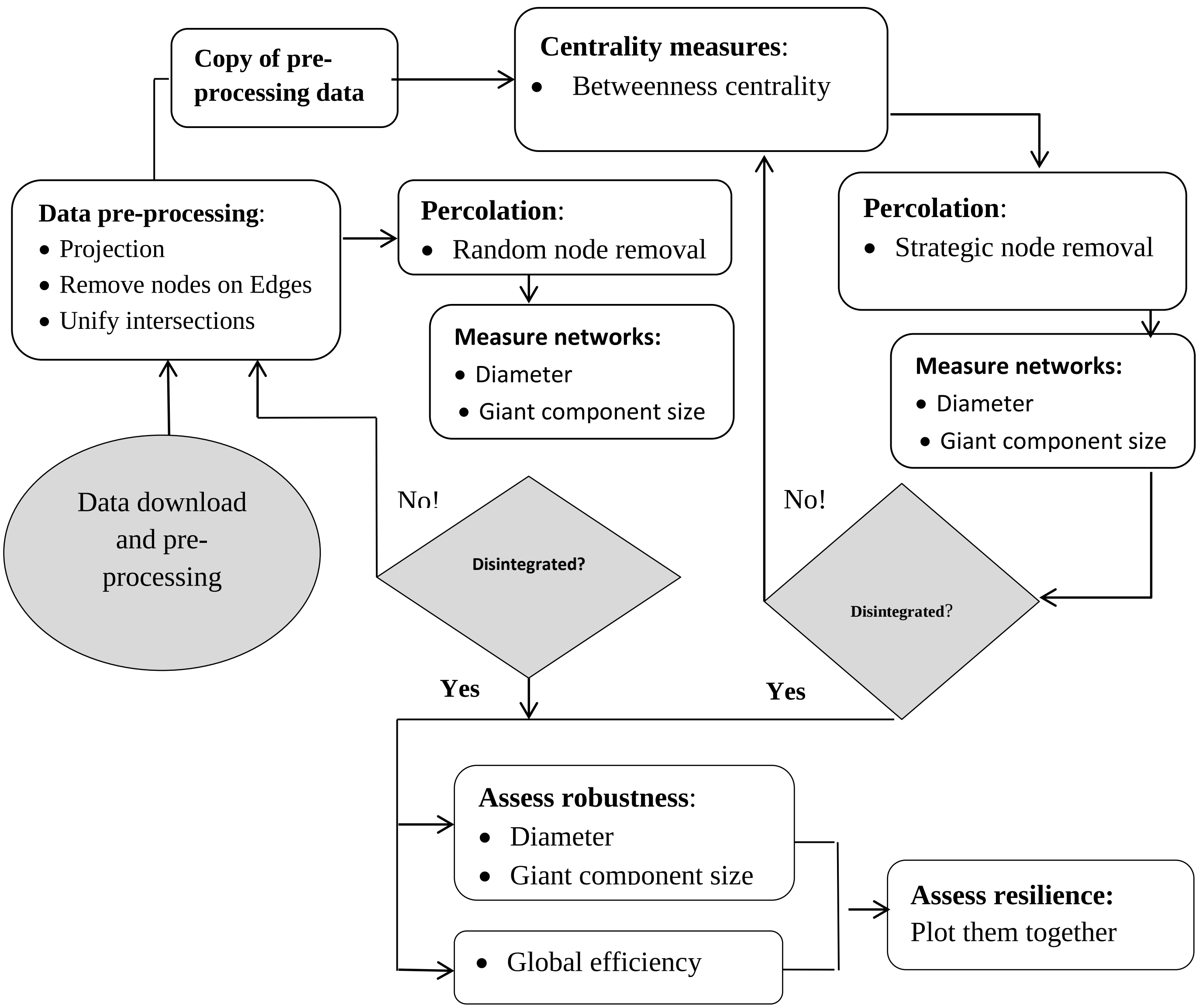


Figure 3.1. *General study methodology flow diagram*

3.2. Data download and pre-processing

In this study, we used an open source tool - OSMnx and networkx - to work with OpenStreetMap (OSM) street network data for robustness and resilience assessment of the Addis Abeba's road network. OpenStreetMap, a collaborative worldwide mapping project, makes its spatial data accessible through different APIs (OpenStreetMap contributors, 2018). On the other hand, OSMnx, a Python efficient research tool, easily downloads OSM data for any place name, location and polygon for analysis and visualization [32] of spatial data. Additionally, using OSMnx, we can download and build topologically correct, project and plot the street networks, and finally saved for advanced use in a shapefile data format.

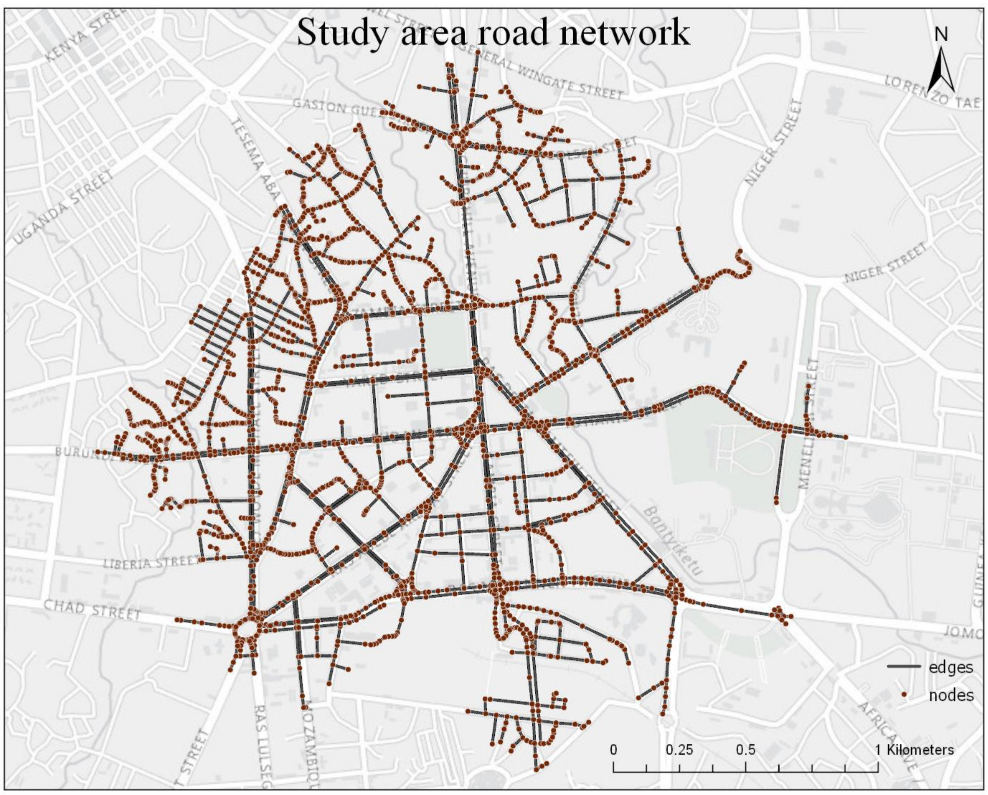


Figure 3.2. *The drivable street network for Addis Abeba, created by passing location query of "9.017043, 38.752561" with 3 km radius into OSMnx.*

Robustness and resilience assessment of the whole city road network in terms of computer processing and time is expensive. Thus, to define the study site and its spatial boundary we use data within 5 km distance to all four directions (North, South, East, and West) from a point location. Based on the researchers supervised knowledge of the city, we use the city hall's location (9.035036, 38.750851) as a center point. Such area coverage of the data is supposed to be a typical road network of the study area.

3.3. Data preprocessing

Data preprocessing (also called data preparation) is imperative when working with OSM data. The main purpose of data preprocessing is to transform the road network data so that the information contained within the data is best prepared for the analysis. Road network data downloaded from OSM has insignificant street curves represented as nodes on the edge of the network, which is not a typical or true node. Those nodes are not typical nodes in the sense of network theory and contribute for petty conclusions about the result. Therefore, we identify and remove those nodes using [32] "simplify" algorithm and merge the set of edges between "true or typical" network nodes into a single edge. Thus, confiscating such nodes from the edge of the network is important before actual network analysis. Additionally, In order to locate and facilitate for later network computation like area, re-projection of the road network data into universal transverse Mercator (UTM) were another pre-process we performed.

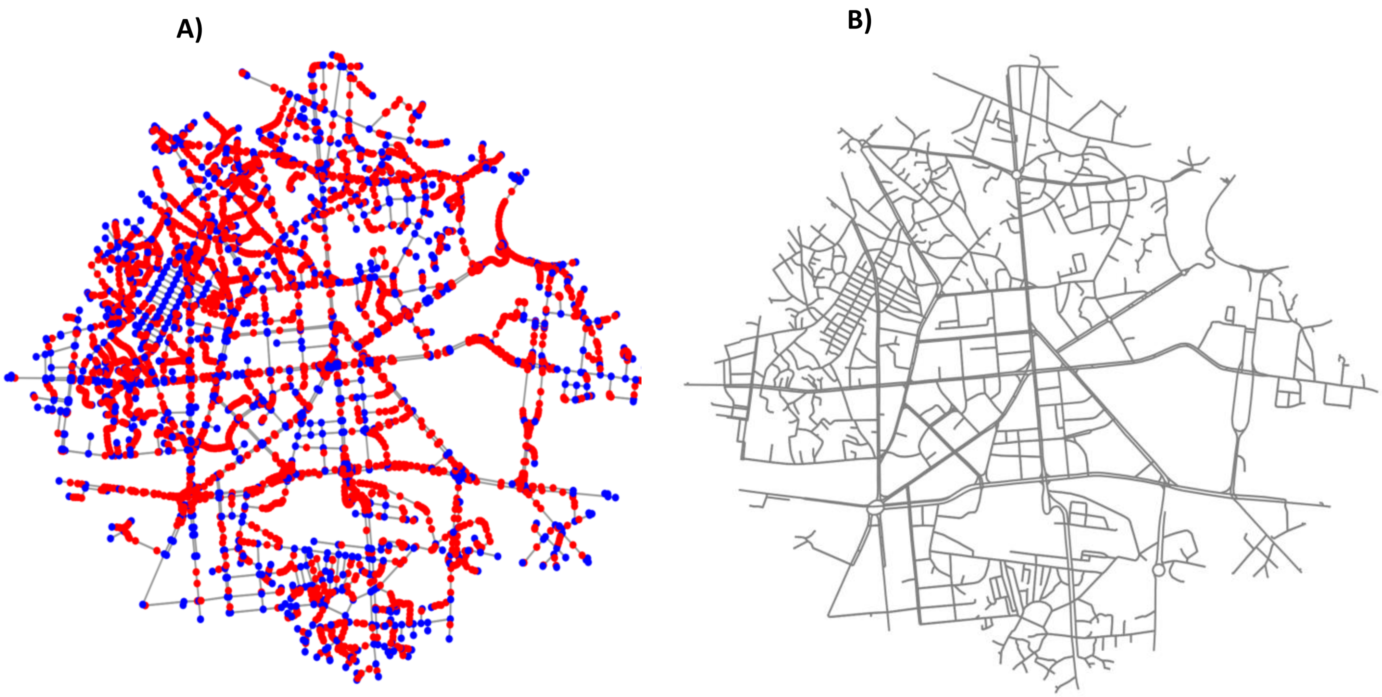


Figure 3.3. *A) non-graph-theoretic nodes highlighted in red and true nodes in blue, B) strictly simplified network,)*

3.4. Betweenness centrality measure

To address the research questions and achieve objectives a centrality measure was implemented from networkx [47] over a pre-processed road network data, as explained in this section below.

In this study, we applied betweenness centrality measures to identify a node with the highest betweenness centrality measure for a strategic node removal purpose. We implement the Ulrik Brandes algorithm ***equation (1)*** of networkx for the most prominent betweenness centrality measurement [23] in assessing the robustness of the road network using the following input parameters:

G	K	Normalized	weight	Endpoints
A Simplified road network	None	True	None	False

Table 3.1. *Betweenness centrality input parameters*

In this case, **G** is a downloaded and simplified road network from OSM and ***K*** is an optional integer value for the number of nodes to consider for estimating betweenness. For ***K***, we use "None" to let the algorithm consider completely simplified road network nodes and get better approximation value. We also normalized the betweenness values by 2/((n-1)(n-2)) for the undirected network where n is the number of nodes in G and 2 is used to make our network un-directed two-way network, the normalization was set to "True".

Since we are working on the networks node, we did not consider edges "weight" for this study. Thus, this parameter was set as "None". Additionally, the endpoints of the edge were not connecting other nodes through a short distance (the main concept behind betweenness centrality is a node used as a bridge) and thus this parameter was "False".

Finally, from such a configuration of betweenness centrality computation, it returns a dictionary of sorted nodes based on the highest betweenness centrality values. To assess the robustness and resilience of the road network, we strategically removed those nodes with the highest betweenness centrality value ***(section 3.4.2)*.**

3.5. Strategic and random node removal

It has been discussed earlier that Addis Abeba's city road network suffers from traffic jam, flooding, and car accidents disturbances. Thus, in order to understand the road networks robustness and resilience against those disturbances; we use the highest betweenness centrality value, computed in ***section 3.4,*** to simulate and remove nodes strategically. We also applied a random node removal technique to assess the robustness and resilience of the road network.

In the case of random node removal, we decided to fail ten nodes and calculate an average dimensional property from these ten failures. This number was chosen because it reflects an optimum maximum and minimum limit of random removal measures. Then again, in order to see how those measurements for ten node removals spread out from the average (mean), we also computed a standard deviation and plot and error bar.

3.6. Road network measurement

After each repetitive strategic and random node removal, using the networkx algorithms, we measure the diameter of the network, giant component size (in this case, a network with a giant component size of 1 is connected and 0 is totally disconnected) and global efficiency until the network is disintegrated (figure 2). We selected those measures because those measures are successfully applied for robustness and resilience assessment ([48],[45], [30], [38] and [37]) & we also believe using those measure will help to clarify the robustness and resilience of the study areas road network.

To evaluate the city's road network robustness (***section 3.7***) and resilience (***section 3.8***) against the strategic and random node removals, we perform a serious of experiments in order to register those measures i.e. diameter, giant component size, and global efficiency**.** Those repetitive centrality measures and node removal experiments depicted in ***Figure 2*** for strategic node removal summarized below:

1. Identify the most significant node using betweenness centrality measure.
2. Remove a node from the network with highest betweenness centrality value.
3. Measure giant component size, diameter and global efficiency of the network after node removal.
4. Recalculate the highest betweenness centrality and remove that node.
5. Then, repeat the above process and register the network measures until the network loses its connectivity.

3.7. Road network robustness assessment

We study the robustness of the road network under random as well as BC based strategic node removal. We analyzed giant component size and diameter of the network simultaneously against the fraction of nodes removed for each node removals i.e. strategic and random node removal (***section 3.6*** & ***figure 4).***

The critical percolation probability *pc* [10] was used to determine the network's robustness i.e. below *pc* the network is going to be not a robust and above *pc*, the network becomes robust network ***(see section 2.3)***. In this way, we were able to assess the road network robustness from the simultaneous analyzes of diameter and giant component size measures against the fraction of the node removed from the network.

Plot (Robustness) 1:

1.1. Plot giant component size from strategic and random node removal against fraction of node removed.

1.2. Plot diameter from strategic and random node removal against fraction of node removed.

Figure 3.4. *Robustness assessment procedure*

3.8. Road network resilience assessment

In this section, we adapt [8] definition of resilience which is a "persistence measure of the network and of its ability to absorb change and disturbance and maintain the connectivity between nodes". To implement this concept, we developed a novel methodology for the assessment of road network resilience by simultaneously analyzing global efficiency and robustness assessments measures. Thus, using this methodology we were able to examine the resilience of the road network by plotting the availability of route using global efficiency against the road network robustness.

a

Plot (Global efficiency):

Plot global efficiency from strategic & random node removal against fraction of node removed.

b

Plot (Resilience):

1. Robustness plot 1.1 vs. Global efficiency
2. Robustness plot 1.2 vs. Global efficiency

Figure 3.5. *Resilience assessment plots. a) Global efficiency measure from strategic and random node removal b) A simultaneous analyze of global efficiency and robustness measures.*

4. RESULTS AND DISCUSSION

4.1. Road network robustness assessment

Giant component size measure

According to ***figure 4.1 A***, a 4% fraction of a strategic node removal from betweenness centrality results in a rapid decrease of the giant component size to 0.0922, which is almost a collapsed network. This study confirms the findings of [33] wherein betweenness centrality based strategic node removal gives worst-case robustness of the road network. Whereas, as shown in ***figure 4.1 A***, robustness measure from giant component size against random node removal shows a progressive decrease of the road networks size. In this case, to completely shutdown the whole network using random node removal, we need to remove 24% of the road network nodes. This situation makes the road network more robust against random node removal than a betweenness centrality based strategic node removal.

The error bar line graph in ***figure 4.1 A*** also shows that the maximum and minimum giant component size standard deviation measures from ten randomly removed nodes was 0.1045 and 0.0007 respectively. Graphically, we can understand that the difference between the maximum and minimum giant component size standard deviation measures between 11 and 20% fraction of node removal is higher than below or above this amount of node removal.

This result demonstrates two things. First, network robustness measure from betweenness centrality based strategic node removal results in a less robust road network than that of robustness assessment from random node removal. Second, the error bar from random node removal in giant component giant component size measurement gives a good impression for taking an optimum random node removal from the network rather than only concluding about road network robustness from one random removal. Generally, the road network was more robust against random node removal than that of BC-based strategic node removal and this result relates with the BC-based node removal robustness experiment result of [49] and [33].

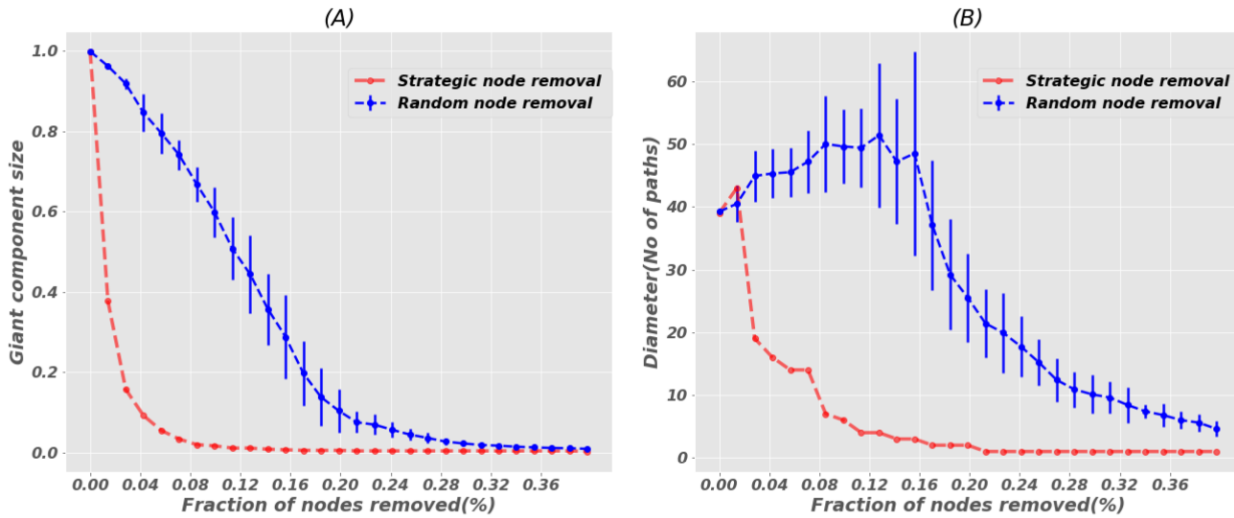


Figure 4.1. *Road network robustness assessment from diameter and giant component size measure against BC-based strategic node removal and random node removal. (A) Giant component size from BC-based strategic and random node removal (B) Diameter from BC-based and random node removal*

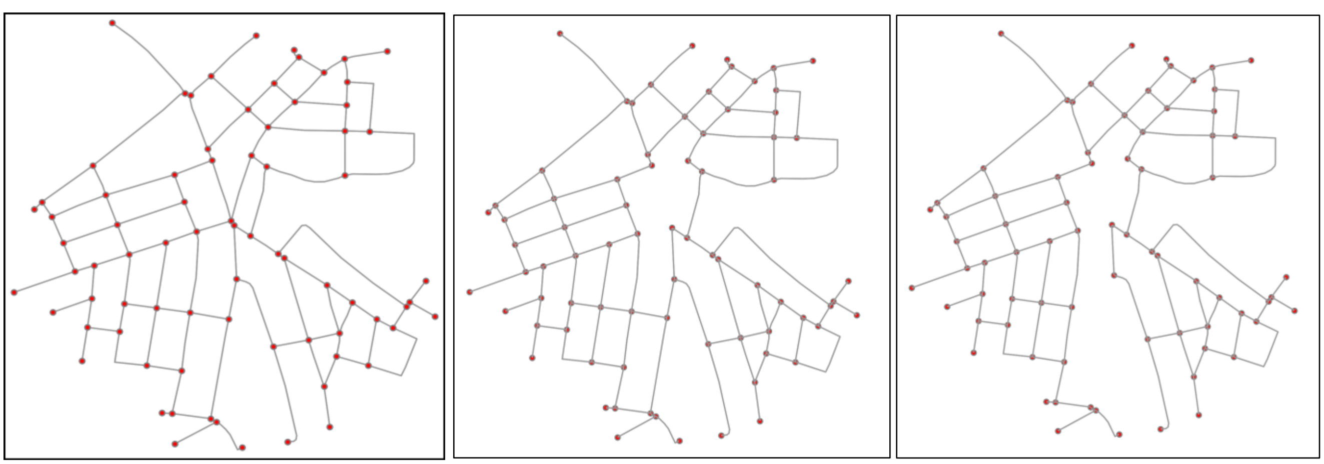
Diameter measure

Figure 4.1 B shows the number of paths needed to complete the maximum distance between all pairs of nodes i.e. diameter for each repetitive strategic and random node removal. In the case of random node removal, approximately 13% fraction of node removal from the network results from 39 to 51 number of path increment to complete the diameter. This increment of diameter indicates the decreasing of the road networks robustness as we apply a random node removal. The remaining fraction of node removal i.e. greater than 13% node removal shows a progressive decrease of paths and this also indicates that as the diameter decreases the road networks becomes more robust.

Interestingly, but perhaps not surprisingly, our result from betweenness centrality based strategic node removal shows a smaller diameter measure than diameter measure from random node removal. In this case, the road networks diameter increases from 39 to 43 numbers of paths against about 3% betweenness centrality based strategic node removal. This situation makes the road network to be less robust against random than strategic node removal. [49] claims robustness of a road network from a small increment of the network's diameter upon the removal of nodes. But, based on the general notion of robustness measurement, road network robustness decreases against strategic node removal, this decreasing road network diameter against BC-based strategic node removal is unexpected.

Despite such a surprising result, thinking better of betweenness centrality and diameter measure relations would offer answers. The network diameter measures the amount of path between two most distant nodes [30] and small diameter entails that all the nodes are just located in a close distance [50]. Thus, based on those thoughts and BC property (***see section 3.4***) we want to argue in a way that it is not always possible to get a robust network with a small or decreasing diameter. We rather need to consider the effect of node removal on the giant component size of the road network.

As we discussed in ***section 3.4***, BC measures the number of shortest paths between node *s* and *t* passing through some node v. When node v with high BC measure removed from the network, all those nodes connected to node v within a short distance either are disconnected or will not be part of a connected network. As the network giant component size decrease, the network diameter also becomes smaller. From this argument, it is not possible to conclude that the road network using the BC strategic node removal in ***figure 4.1 B*** is robust or not robust. We rather prefer to experiment further, ***figure 4.2 & 4.3***, in a way that the conclusion about BC based robustness measure using diameter i.e. an increasing diameter for non-robust network and decreasing diameter for the robust network has different implications. Accordingly, we took two-network types i.e. better connected (***figure 4.2)*** and less connected network (***figure 4.3)*** and assess how robustness measure responses from strategic node removal using diameter.



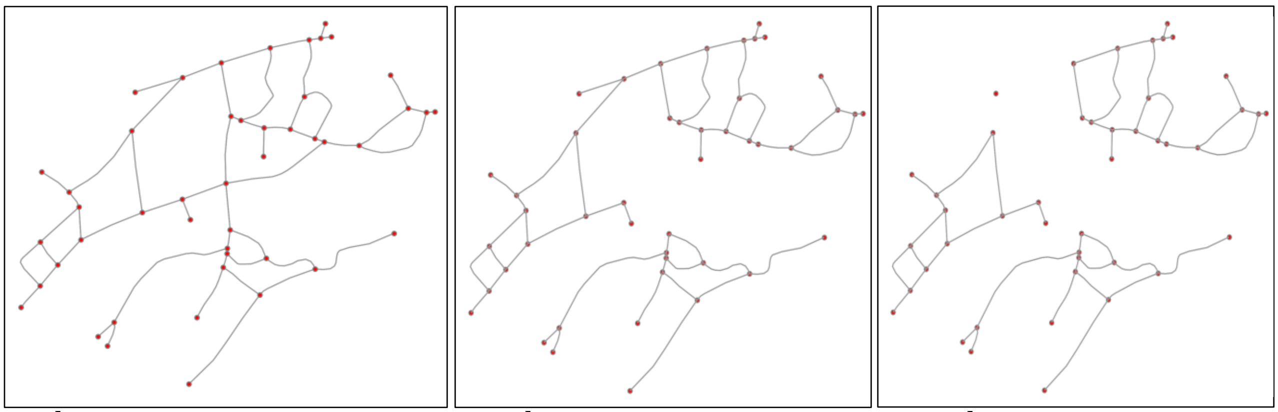
Node: 77
Edge: 214
Diameter: 13 paths

Node: 76
Edge: 216
Diameter: 15 paths

Node: 75
Edge: 200
Diameter: 20 paths

*Figure 4.2***:** Diameter measure change from betweenness centrality based node removal (relatively well-connected network).

As we can see in ***figure 4.2***, a well-connected network exhibits the presumed robustness measure i.e. an increasing diameter for non-robust network against BC based node removal. However, a less connected network on ***figure 4.3*** shows the same trend of diameter change as the actual network study in response to a strategic removal of nodes. Thus, from this experiment, we can conclude that a decreasing diameter measure in response to BC based strategic node removal does not always show a robust network. The physical structural connectivity (***as shown in figure 4.2 & 4.3***) also determines the robustness measure-using diameter.



Node: 47	*Node: 46*	*Node: 45*
Edge: 114	*Edge: 106*	*Edge: 100*
Diameter: 11 paths	*Diameter: 15 paths*	*Diameter: 8 paths*

Figure 4.3: Diameter measure change from betweenness centrality based node removal (relatively less connected network)

Robustness comparison from diameter & giant component size measures

As we discussed in ***section 4.1*** about ***figure 4.1 (A),*** based on the first diameter measurement of the road network against BC-based strategic node removal and random node removal diameter, the network was considered more robust against strategic node removal. Nevertheless, when the amount of node removal from BC-based strategic node removal increases, the diameter of the network abruptly decreases and this leads us for a presentation of different argument regarding diameter measure for robustness measure from BC-based node removal.

According to ***figure 4.1 (B),*** the effect of the BC-based strategic node removal was visible and the giant component size drops abruptly whereas random node removal demonstrates a progressive decrease of the network giant component size. Therefore, the road network was less robustness against BC-based strategic node removal than random node removal and additionally, assessing the road network robustness from diameter measure of the road network against BC-based node removal not recommended.

4.2. Road network resilience assessment

Figure 4.4 shows that a BC-based strategic node removal results in a sharp decrease in the availability of a route, from global efficiency measure than random node removal. Removing node randomly results for better availability of the possible route and show a progressive decline before the network completely collapse. Thus, BC-based strategic node removal results for a better understanding of the road network's weakness against strategic attacks like a terrorist attack. Accordingly, identifying and managing those weaknesses helps to assure the availability of services like economical and social services using the city road networks route.

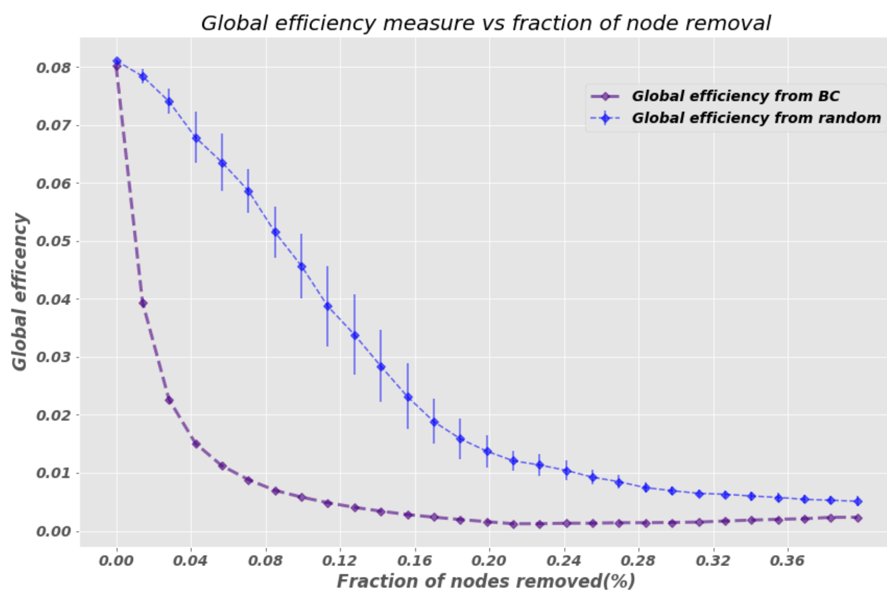


Figure 4.4: Global efficiency measure from BC-based strategic and random node removal

Resilience assessment from the giant component size and global efficiency

According to **figure 4.5**, in response to about 2% fraction of node removal, both giant component size and global efficiency show the same changes. However, strategically removing 2% - 16% of the node from the road network results in a quick drop of giant component size and a relatively slow change of global efficiency.

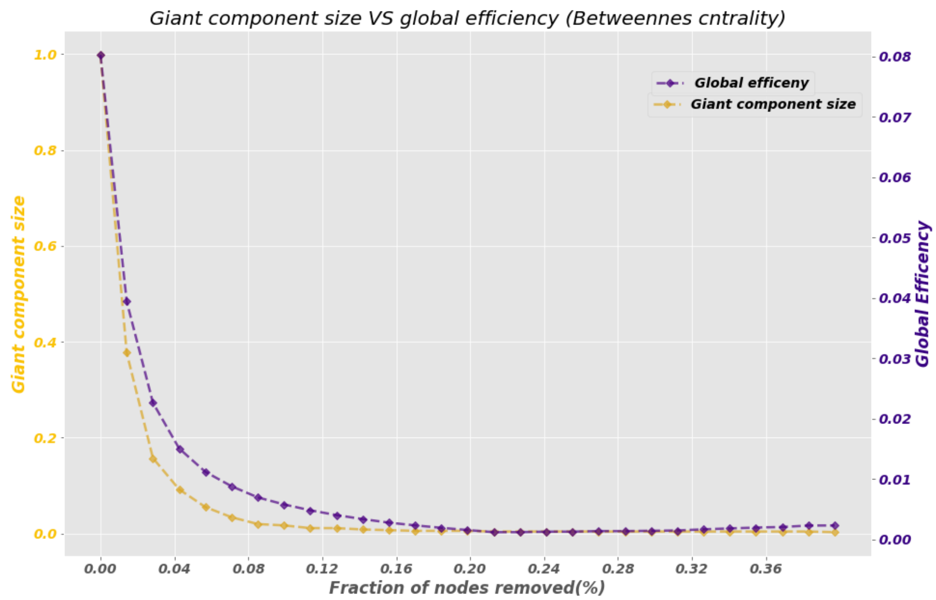


Figure 4.5: Road network resilience measure from the giant component size and global efficiency against betweenness centrality based strategic and random node removal.

Thus, even though the giant component size declines too fast from the beginning of the strategic node removal, global efficiency measure shows some persistence between 2% to 16% fraction of node removal. The global efficiency persistence in maintaining route helps to have some availability of route within the network before the network completely collapsed. From this, it is possible to conclude and suggest that we can achieve resiliency from a small sized network than the big sized network. At the same time, based on global efficiency measure and BC-based strategic node removal, removing 2% - 16% fraction of nodes results in a slight availability of route than 2% node removal

Resilience assessment from diameter and global efficiency

According to ***figure 4.6,*** as diameter measure increase from 39 to 43 paths against 3% fraction of node removal from BC-based strategic node removal, global efficiency measure drops declines faster. In ***section 4.1*** about ***figure 4.1*** (B), we argued about the response of the network against BC-based strategic node removal in measuring the diameter. Thus, the decreasing measure of diameter from BC-based strategic node removal does not mean that the road network is robust against BC-based strategic node removal. Since BC considers nodes that are connected to a node within the shortest distance, by apply BC-based strategic node removal it rather shows the disintegration of the network and formation of the smaller connected network. Generally, as diameter measure from BC-based strategic node removal shows a decline the network early loses its resiliency from global efficiency measure.

Accordingly, while the network forms a small-connected network, the application of BC-based *strategic node removal* results for a less resilient network. The global efficiency measure from *strategic node removal* decreases as the number of paths needed to complete the maximum shortest distance i.e. diameter decreases.

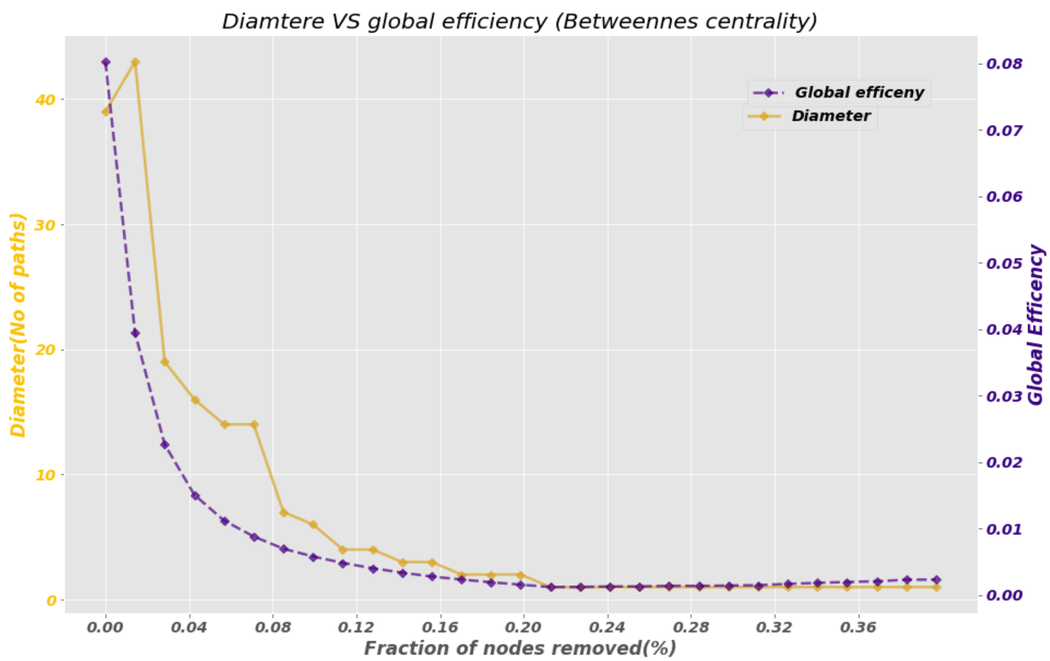


Figure 4.6: Road network resilience measure from diameter and global efficiency (G.efficiency) against betweenness centrality based strategic node removal.

4.3 Limitations

This study was backfired by large processing time and a need for high computation computer. Because of this problem, we were not able to apply to a large area. Additionally, It was a great relevant to the study and compare with other cities, other areas (urban, rural), or other countries. Thus, the scalability of the study was not addressed.

5. Conclusion

Road network robustness is an important property of the network that determines the resistance of the network against strategic and random node removal. Due to the increasing probability of the road networks exposure to strategic and random actions, assessing this property of the road network against those actions becomes the first priority to pinpoint and generalize the susceptibility of the network and set significant management options. Resilience is also the other measure of the networks extended functionality even after it loses its robustness. Combing those two measures, robustness and resilience give an ample understanding of the road networks status.

A centrality measure of a network helps to identify the most significant node for the assessment of the road networks robustness and resilience. Centrality measures are of different types with a different concept and application needs. Among those, betweenness centrality measures are the most commonly used centrality measure in robustness and resilience assessment that considers the location of a node within the shortest distance from the other nodes. This centrality measure used to simulate the most important nodes in a network for later removal as an example of strategic node removal. Besides a centrality measure, randomly removing nodes from the network simulates any accidents that happen on the network random node. Thus, removing nodes by applying those measures and then measuring the networks change in terms of the networks physical property like diameter, giant component size and efficiency help to assess the networks robustness and resilience properties.

In this study, we implement the above-mentioned concepts in order to assess the robustness of the road network for assessment of the road networks resilience. From giant component size measurement, a 20% fraction of node removal using random node removal techniques makes the road network robust than betweenness centrality based strategic node removals which only need a 4% fraction of the networks node to be removed to collapse the whole network. The robustness analyses using diameter measure also shows that the networks diameter increases from 39 to 51 paths in case of random node removal while the diameter increases from 39 to 43 paths from strategic node removal. As we tried to argue in the result section of the document (section 4.1) that diameter, this result does not pass the correct message about robustness.

The reason is that, since both diameter and betweenness centrality measures depend on a measure of distance, the notion of increasing diameter from betweenness centrality based strategic node removal was not observed. BC considers a node within the shortest path and removal of this node collapse the size of the road network. We rather need to suggest that using diameter for robustness analysis of a road network is not a good measure.

From the simultaneous analysis of robustness and global efficiency measures, we were able to assess the road network resiliency. As shown in ***figure 4.5***, from the giant component size measure the network becomes less resilient as the giant component size decreases. However, when the fraction of nodes removed from the network is 2 to 16%, the network shows some perseverance in the availability of route from global efficiency measure. As shown in figure 4.3, at this stage of node removal, the network was almost a collapsed network and thus, it is difficult to say that the road network is resilient. In conclusion, greater than 88% (***figure 4.1, 4.4, 4.5 & 4.6***) of the network was vulnerable for both strategic and random node removal and were not able to be robust and resilient as well. Thus, from this miniature research, we believe that this finding gives an ample understanding of the cities road network robustness and resilience as well and the city planners and administrators can infer about the need of the cities road network re-design and expansion activities. Additionally, this study helps them to see that the city's road network is more vulnerable to betweenness centrality based strategic attack than randomly attacking the road network.

Future work

From this study, we also come up with further research areas. Future research should consider the potential effects of removing more than one node and taking the average measure of some sample of a node in case of random node removal more carefully. For example, a network giant component size measure form only one random node removal and from the average of some amount of randomly removed node does not have the same effect on the network giant component measure. Since there is no methodology for choosing a sample of random removals for a certain size of network it will be a huge input for the network science community. Future researches on robustness measure by extending physically visualize and see the cascading failure after strategic and random node removal will a huge topic.

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