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Strategic Prioritization of Pedestrian Road Maintenance Using Multi-Criteria Decision Analysis in QGIS and Python

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Abstract

Improved and well-maintained pedestrian roads are the backbone of guaranteed safety, accessibility, and rejuvenation of urban infrastructure. The study takes into account the road network, geographic analysis, and multi-criteria decision-making (MCDM) framework with the ELECTRE IV method to prioritize the pedestrian road maintenance in Genoa-Italy. Some of the criteria studied are vertex degree D(v) (), betweenness B(v) , cut vertex , the number of critical buildings , vulnerable population , and cost . All of which are the aspects related to network connectivity, vulnerability, and financial feasibility that need to be addressed together.

In the entropy method, which was used, each fine-tuning threshold is the general rule of the synthesis of all information. The cut-vertex becomes a precious criterion as it is the one that, if missing, network cohesion will be disturbed.

The normalization of the decision matrix brought about the formation of the concordance and discordance matrices, which in turn allowed for the establishment of a dominance matrix to prioritize the sections of the roads based on their necessity.

It is possible to adapt the ELECTRE IV method by adjusting concordance and discordance thresholds to prioritize the process in a fine way. This non-compensatory decision-making approach is utilized as no single criterion can entirely counterbalance another.

The results throw a clear light on the road sections which need to be given priority, and thus maintaining network integrity to serve vulnerable populations is the most important key point.

This study provides a significant decision-support tool to urban planners. They can make an informed and transparent maintenance decision by the help of this.

Preface

The need for efficient and effective pedestrian road maintenance strategies has become increasingly critical in our rapidly urbanizing world. Keeping an infrastructure that becomes old and increases the volume of traffic on the road would be sustainable and cost-effective. These sustainable and cost-effective methods are increasingly in demand. This thesis seeks to address these issues through the exploration of creative strategies and approaches to pedestrian road maintenance and life extension.

This study was made possible mainly through the guidance and support of other people. I am deeply indebted to my professor, Prof. Elvezia Maria Cepolina, for her brilliant guidance, critical evaluation, and constant help during this endeavor. Her words of encouragement and volunteerism are so important.

This thesis presents my academic work and my contribution to pedestrian road maintenance. I strongly believe that the suggestions and ideas expressed in this document will feed evolution and thereby to further research and practice ultimately leading to more sustainable and effective management solutions.

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Chapter 1: Introduction

Multi-criteria decision-making (MCDM) as a branch of operations research can be interpreted as a problem-solving process terminated by a solution considered to be optimal by explicitly evaluating the feasible alternatives over conflicting multiple criteria in decision-making. MCDM problems intensively applied in many disciplines, including social sciences, economics and medical sciences (Peng et al. 2014; Pramanik et al. 2016; Singh et al. 2016;
Zhan et al. 2018a, b). In recent years, various models, such as TOPSIS (Hwang and Yoon 1981), PROMETHEE (Brans et al. 1986), ELECTRE (Benayoun et al. 1966), VIKOR (Opricovic and Tzeng 2004), KEMIRA (Krylovas 2014), have been presented to efficiently solve the MCDM problems that arose in daily life. ELECTRE (Elimination and Choice Expressing REality) method, initiated by (Benayoun et al. 1966) and (Roy 1968), is one of the most effective decision-making techniques based on pairwise comparison of actions by outranking relation and provide as much as possible precise and suitable set of actions by eliminating the alternatives which are outranked by others, with respect to multiple criteria. In the decision-making process, an alternative a_1 outranks other alternative a_2 if, considering all available information related to the underlying problem simultaneously that there is acceptable evidence to believe in the conclusion that a_1 is at least as better as a_2 and there does not exist any strong argument in opposition. MCDM not only is used for simplifying and achieving a clear decision but also allows researchers and managers to achieve a balance between different opposing criteria (Govindan et al., 2015). All decision-aided techniques based on outranking relations rely on two major concepts: concordance and discordance, which exhibits in a particular sense, the reasons for and against an outranking situation. There exists vast literature involving study and extensions of ELECTRE method such as: ELECTRE II, ELECTRE III, ELECTRE IV, ELECTRE IS and ELECTRE TRI (Figueira et al. 2005). ELECTRE method has been applied in many fields of real life; readers are referred to Aiello et al. (2006), de Almeida(2007), Beccali et al. (2003), Botti and Peypoch (2013) and Rogers and Bruen (1998).

In the traditional ELECTRE models, the judgments on the alternatives and the relative importance ratings for each of the criteria are crisp and precise. ELECTRE, along with its many iterations, is an outranking method based on concordance analysis. Its major advantage is that it considers uncertainty and vagueness.

The objective of this study is to plan the maintenance of various damaged pedestrian infrastructures in order to prioritize the most critical ones and then to plan the maintenance of them.

Comfortable pedestrian infrastructure, connected to destinations of interest, safe, accessible, equitable, and sustainable transportation system. Planners recognize the benefits of providing well-maintained sidewalks but often there is lack of maintenance management systems which is necessary to prioritize sidewalk maintenance.

Almost every trip made on the transportation network begins and ends with a walking trip on a sidewalk. The presence and quality of sidewalks predict safety and general satisfaction in the pedestrian environment.

To rank the alternatives, a multi-attribute decision-making method (MADM) is proposed in which the alternatives compared are predetermined and part of a finite set. Alternatives are not mutually exclusive because with a given budget the decision maker can afford more than one intervention, depending on the costs. So, once the ranking has been done, we define the cluster of interventions that will include the first ones in the ranking as long as the budget is sufficient to realize them.

Structure of the thesis

- The master thesis is structured as follows. Chapter 1 provides a brief description of the thesis work, problem statement, highlighting the purpose of the work, the goal to be achieved, and the proposed solution.
- Chapter 2: Provides a more detailed explanation of concepts and techniques required in the implementation of the work. This chapter includes two sections: First, criteria assessment methods with a review of the Network Analysis Model as the methodology for topologic measurements, and all assessment methods, the second section is a review of the ELECTRE technique, including an overview of outranking relations in the ELECTRE methodology, and with an explanation of the concordance index, its formulation, concepts and some extensions to its operation.
- Chapter 3, makes an empirical analysis of alternatives and assesses the concordance values exploited to obtain a ranking of alternatives, summarizes the work, and discusses the main conclusions of the work and possible future work to be done.

Research problem Statement

Pedestrian maintenance is a critical aspect of urban infrastructure management, directly impacting the safety, accessibility, and longevity of pedestrian pathways. Sidewalks, as an integral part of urban pavements, require consistent monitoring and maintenance to prevent hazards such as cracks, potholes, and surface degradation. Lack of automated prioritization is not only time-consuming but also prone to human error, leading to inefficient maintenance schedules and potentially hazardous conditions.

With the advent of advanced technologies, there is an unprecedented opportunity to revolutionize pavement maintenance strategies.

Pavement damages pose significant risks to pedestrians, leading to potential injuries such as trips, falls, sprains, and fractures. These hazards are particularly dangerous for vulnerable populations, including the elderly, children, and individuals with mobility impairments. Uneven surfaces, hidden potholes, and other sidewalk defects can also impede the movement of wheelchairs, strollers, and other assistive devices, further compromising accessibility.

Aims and Objectives

1. Automate prioritize formulation with the multi-criteria approach for pedestrian network maintenance management.
2. Development of a decision support system, and selection of appropriate maintenance strategies, for the pedestrian network.

Sidewalk infrastructure is a critical component of sustainable transportation systems. The presence and quality of sidewalks are significant predictors of perceived safety and general satisfaction in the pedestrian environment. Furthermore, sidewalks are a vital component of accessible transportation infrastructure designed to improve the quality of life of people. The effective management of infrastructural networks in case of a crisis requires a prior analysis of the vulnerability of the network and identification of critical locations.

Pedestrian road maintenance includes various types of corrective and preventive maintenance strategies. In this study, we consider the strategy for corrective maintenance that applies when the pavement is structurally deficient. Depending upon the condition of the pavement, suitable maintenance needs to be planned. Delaying the maintenance causes not only a risk of incidence but also increases maintenance costs. Maintenance planning can be applied at the network level where the objectives are towards assessment of budget requirements, setting maintenance priorities, and schedule of the projects for maintenance. This study presents an operation-research model to evolve the optimal solution for the maintenance scheduling of a pedestrian network.

Proposed Solution:

A hierarchical structure is constructed to apply the algorithm. Relationships among criteria and sub-criteria are determined and reflected in the hierarchical model shown in Figure 1. The hierarchical structure of the maintenance strategy includes four levels. The first level of the hierarchy represents the final goal of the problem, while the second level of the hierarchy consists of three main selection criteria. These criteria are decomposed into various sub-criteria. Finally, the bottom level of the hierarchy represents four alternatives for applying maintenance strategies.

Our study will be considered in two parts. The first part refers to considering the main criteria which are: Network connectivity, users and their vulnerability, and Cost. these criteria were first assessed and weighted and then in the second part, they ranked by using the ELECTRE method. Take into account that by increasing Network connectivity and Users & their vulnerability, maintenance priority will be increased but by increasing the cost, priority will be decreased.

The Goal Function P is:

$$\text{Maximize } P = w_1C_1 + w_2C_2 + w_3C_3$$

S.T:

$$w_1 + w_2 + w_3 = 1$$

$$w_1 = (w_{D(v)} + w_{B(v)} + w_{cut\ vertex}$$

$$w_2 = w_{VP} + w_{CB}$$

$$C_1 = (w_{D(v)} * D(v)) + (w_{B(v)} * B(v)) + (w_{cut\ vertex} * cut\ vertex)$$

$$C_2 = (w_{VP} * VP) + (w_{CB} * CB)$$

The main criteria, each with sub-criteria are shown in Figure 1.

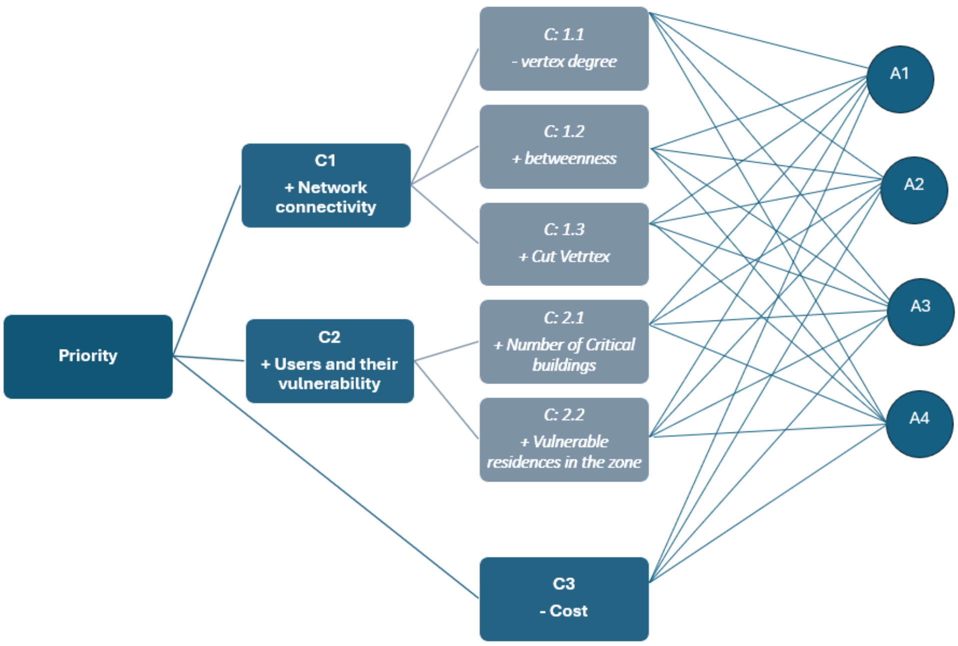


Figure 1: Hierarchical tree of the set of criteria

1.1.1.Network Connectivity:

It is a fundamental concept in urban planning, transportation, and network theory. It refers to the degree that shows how different parts of a system are connected, allowing for the efficient movement of people. In urban and transportation contexts, connectivity typically describes how well different locations within a city or region are linked by a network of roads, pathways, or public transit routes. High connectivity enables easier and more direct travel, fostering economic activity, social interaction, and access to services. In essence, connectivity is about ensuring that the components of a system are well-integrated, facilitating seamless interaction and movement within the network. We use Network Analysis Models for our analysis.
Data was extracted from the "OpenStreetMap" website, and calculations were done by coding in Python.

1.1.2.Users and Vulnerability

Urban environments are dynamic and complex, characterized by intricate networks that facilitate the movement of people. Among these, the pedestrian network is a critical component, enabling safe and efficient movement for individuals within cities. However, this network is often vulnerable to a variety of disruptions, including natural disasters, accidents, and urban congestion. The vulnerability of pedestrian networks is a significant concern, particularly in areas with high flow rates and proximity to critical buildings such as hospitals, schools, and government facilities.

Understanding and predicting the vulnerabilities within pedestrian networks is crucial for urban planning. High pedestrian flow rates, especially in dense urban areas, can exacerbate the impact of disruptions, leading to congestion, delays, and even accidents. Additionally, the presence of critical buildings adds another layer of complexity, as these structures often serve essential functions during emergencies.

Prediction models that assess the vulnerability of pedestrian networks can provide valuable insights for urban planners, helping to identify potential weaknesses and develop strategies to mitigate them. We use QGIS (Quantum Geographic Information System software) as an analytical tool designed to help us assess and forecast the vulnerability of pedestrian networks.
Data extracted from the "OpenStreetMap" website, was calculated and analyzed with QGIS software and Python coding.

1.3.3. Cost

Since lower cost generally means a more favorable outcome for maintenance prioritization (i.e., lower cost is better), we need to categorize it as a cost criterion. It means by increasing the cost its importance decreases. Since the calculation of the cost is out of the thesis's scope, we randomly assign a cost to each alternative.

Example:

Suppose you have costs of €10,000, €15,000, and €20,000 for three projects. You could normalize them by ranking or scaling them so that lower costs get higher scores (e.g., 5 for €10,000, 3 for €15,000, and 1 for €20,000).

Chapter 2: Methodology

2.1. Section 1: Criteria Assessment Methods

2.1.1. Network Analysis Model

Linear geographic phenomena can be modeled as spatial networks. Such network in Geographic Information Systems (GIS) is represented by graphs: the intersections and bending points of linear features are represented as vertices and the features themselves as edges that connect the vertices (Worboys and Duckham 2004). Using graph theory for the analysis of these phenomena is therefore a logical choice. Much has been done in this area, in transportation (Thill 2000, Miller and Shaw 2001), but many of the GIS applications only use traditional methods, such as finding the shortest path, calculating the flow capabilities, or analyzing the connectivity of a network to correct the data if the network turns out to be unconnected (Curtin 2007). More complex analyses using tools from other areas of graph theory, such as probabilistic graph theory, complex networks research, algebraic/ spectral graph theory, and structural graph theory are rarely used. Advanced applications of graph theory are therefore not as common in GI Science as in other disciplines, where graphs represent various phenomena, including organic molecules in chemistry, protein receptor interaction networks in medicine, genealogies, Internet networks, citation networks, and diffusion networks of diseases (Batagelj and Mrvar 2003). The approach which combines dual graph modeling with measures from structural graph theory, probabilistic graph theory, and complex networks research with several advanced graph theoretic concepts, presents an analysis of spatial networks (urska 2008)

One of the oldest fields of application is social network analysis (de Nooy et al. 2005), where the three centrality measures were first defined (Freeman 1979). In social networks, vertices represent persons or institutions, and the links refer to relationships between them. The vertex *degree* in social network analysis describes the data reachability of a person in the network: how easily can information reach that person? *Betweenness* describes the extent to which the person is needed as a link in the chains of contacts that facilitate the spread of information in the network. If a person with high betweenness is removed from the network, many flows of information are disrupted or must take longer detours (de Nooy et al. 2005). Besides these classical centralities, several other centrality measures can be used for analyzing the structure of a social network (see Borgatti and Everett 2006 for a review of various centralities in social network analysis) and these principles can also be used for spatial phenomena (Besussi 2006).

In complex network research, many studies have been undertaken to examine the vulnerability and survivability of critical network infrastructures. Some studies offer to focus on global, continental, or national networks, such as the Internet, electrical power systems, and airport networks and either examine their scale-free or small-world properties or analyze their flow capabilities (Carlier et al. 1997, Latora and Marchiori 2004, Grubesic and Murray 2006, Guida and Maria 2007, Murray et al. 2007). The Internet in the USA is an example of a spatial information network that has received a particularly thorough investigation (Wheeler and O'Kelly 1999, Gorman and Malecki 2000, O'Kelly and Grubesic 2002, Grubesic et al. 2003, Gorman and Kulkarni 2004, Gorman et al. 2004).

Network Analysis Models are indispensable tools for analyzing and optimizing complex systems where interconnections play a pivotal role. It can be represented as networks. These models are rooted in graph theory, where systems are depicted as a set of nodes (vertices) and edges (links) that connect them. The nodes typically represent entities such as intersections in a transportation network, buildings in urban planning, or species in ecological networks, while the edges represent the relationships or connections between these entities, such as roads, pathways, or interactions.

What is Network Analysis?

Network Analysis involves examining these nodes and edges to understand the underlying structure of the network, the flow of resources or information through it, and the robustness of the network to changes or disruptions. By applying network analysis, one can uncover patterns such as clusters of highly interconnected nodes (communities), identify critical nodes that play a central role in the network (centrality), and assess the overall connectivity and efficiency of the network.

Why and When do we choose Network Analysis Models?

Network Analysis Models are particularly valuable in situations where the relationships between components of a system are as important as the components themselves. This makes them applicable in a wide range of fields, including:

- **Urban Planning and Transportation**: To optimize traffic flow, improve public transportation routes, and enhance pedestrian connectivity.
- **Ecology and Environmental Science**: To study the connectivity of habitats, the spread of species, or the impact of environmental changes on ecosystems.
- **Social Network Analysis**: To understand relationships and influence within social groups, identify key influencers, and model the spread of information.
- **Infrastructure and Resilience Planning**: To assess the vulnerability of critical infrastructure networks (e.g., power grids, water supply networks) and plan for disaster resilience.

These models are chosen when there is a need to go beyond isolated data points and consider the interdependencies within a system. For instance, in urban planning, it's not just the number of roads or buildings that matter, but how they are connected and how efficiently people can move through the city. Network analysis provides a structured way to evaluate these connections and optimize them for better outcomes.

Advantages of Network Analysis Models

- **Comprehensive Understanding**: Network analysis allows for a holistic view of the system, revealing the complex interrelationships between different components that might not be apparent through traditional analysis methods.
- **Identification of Critical Nodes**: By analyzing centrality metrics, these models can identify key nodes crucial for the network's functioning. This is vital for prioritizing investments or protecting critical infrastructure.
- **Optimizing Resource Allocation**: Network analysis helps in efficiently allocating resources by identifying optimal pathways or connections, reducing costs, and improving performance.
- **Predicting and Mitigating Disruptions**: By simulating the effects of node or edge removal, network analysis can predict how disruptions (e.g., road closures, habitat loss) will impact the network, aiding in the development of robust contingency plans.
- **Scalability and Flexibility**: These models can be applied to networks of any size and can be scaled up as the complexity of the system increases. They are also flexible, allowing for the incorporation of various types of data and relationships.

Key Concepts in Network Analysis Models

Graph Representation:

- **Nodes**: In the context of a pedestrian network, nodes could represent specific locations such as intersections, entrances to buildings, or key points along a pathway.
- **Edges**: Edges connect the nodes and represent the pathways pedestrians can wake, such as sidewalks, footbridges, or crosswalks.

We use this powerful model to evaluate and understand the structure and connectivity of pedestrian networks. These models rely on concepts from graph theory [1], where the pedestrian network is represented as a graph consisting of nodes (representing intersections, crosswalks, entrances/exits of buildings, etc.) and edges (representing pathways, sidewalks, or pedestrian routes).

2.1.2. Assessments Base on Graph Theory:

This section presents the mathematical method for the identification of critical locations in a spatial network. The approach is based on graph theory and uses the topology of the network (i.e. how the segments in the network are connected) in order to identify problematic elements. The geometry of the network elements (meaning the actual spatial location of the streets) has been used for visualization purposes, but the method does not use any attribute information.
The connectivity graph where vertices represent named streets and edges intersections between streets is sometimes called the dual modeling approach for the street network (Crucitti et al. 2006)
The method combines dual graph modeling with connectivity analysis and two topological graph measures: 'betweenness', and 'vertex Degree'.
The approach presented in this study attempts to identify critical locations in a spatial network by using *its line graph*. The network is represented as an *undirected* and *unweighted graph G* from *which its line graph L(G) is derived*. Critical locations correspond to edges in the original network, but *since the centrality and topological measures can only be calculated for* vertices and not for edges, we initially *translate edges into vertices* by generating a *line graph.*
The procedure is based on the assumption that the *vertices of the line graph* that correspond to critical locations have one or more of the following three properties:

- They are cut vertices of the line graph
- They have a high betweenness
- They have a low vertex degree

All cut vertices are critical locations.
Betweenness is linked to the flow in the network, removing a vertex with high betweenness from the line graph is equivalent to removing an edge with a high edge-betweenness from the original graph. This breaks off many shortest paths between vertices in the original graph, which disrupts the flow or redirects it through a longer detour. This is one of the essential properties of a critical location. It is therefore reasonable to use high betweenness in the line graph as one of the criteria for the identification of critical locations.
The vertex degree is a measure that considers the immediate neighborhood of a vertex.

2.1.2.1. Basic Definitions from Graph Theory:

A *graph* G = G (V, E) is a pair of two disjoint finite sets V and E, where E is a subset of V×V, which means that it is a set of two-element subsets of V. The elements of V are *vertices*, and the elements of E are *edges*. An edge *e=uv* from the set E connects vertices *u* and *v*. When representing this structure graphically, the vertices are usually drawn as dots and edges as lines connecting the two respective vertices. Two vertices x, and y of G are *adjacent* or *neighbors* if xy is an edge of G. Two edges of G are *adjacent* if they share a common end vertex. If no direction is specified on the edges (i.e. the edge *uv* is considered the same as the edge *vu*), then the graph is *undirected.* If the direction of the edge is important, then the graph is *directed.* The vertices and the edges can also have numerical or other values assigned – this is a *weighted graph,* and these values are called the *weights*.[9]

At this point in the development of our method, <u>we are only interested in *undirected* and *unweighted* graphs.</u>

Line Graph: When *properties of edges* need to be translated into *properties of vertices*, calls "*line graph"* is usually constructed. Given a graph G, the line graph L(G) takes the *edges of G*, *as its vertices*, i.e. [3]

V(L(G)) = E(G). Two vertices *e* and *f* in the line graph are connected if and only if the respective edges e and f are adjacent in G (i.e. they share a common end vertex). [3]

Figure 2 shows an example of a graph G and its line graph L(G).

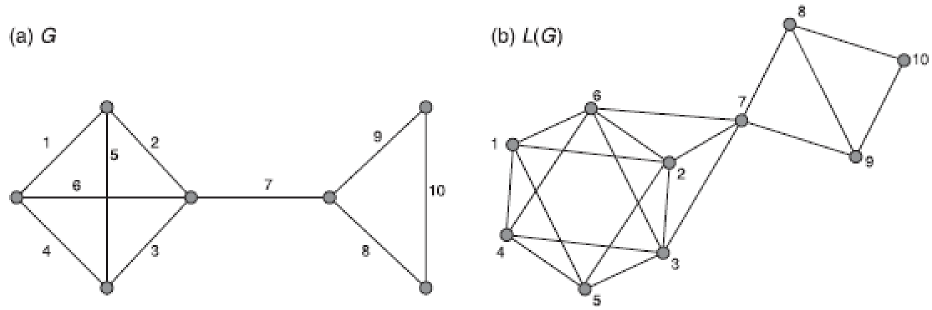


Figure 1: (a) Graph G and (b) its line graph L(G). the edges of the graph G are labeled with the same numbers as the corresponding vertices in its line graph L(G)

A walk in a graph is an alternate sequence of vertices and edges, v_1, e_1, v_2, e_2, …, v_n, where each edge e_i, connects vertices v_i and v_{i+1}, trail is a walk in which no edge is repeated. A path is a trail in which no vertex is visited more than once. The length of a walk, a trail, or a path is defined as the number of edges it contains.

Two vertices *u* and *v* of an undirected graph G are connected if G contains a path from *u* to *v*. A graph is connected (or vertex-connected) if every two vertices of the graph are connected (i.e. there exists a path between every two vertices in the graph).

We used the Python library "nx.line_graph(graph.to_undirected()" which converts our original graph into an undirected graph (if it wasn't already) and then creates a line graph. In a line graph, nodes represent edges of the original graph, and two nodes are connected if the corresponding edges share a common node in the original graph.

2.1.2.2. Degree of vertex:

The vertex degree in a network, often denoted as d(v), is a fundamental concept in graph theory and network analysis. It refers to the number of edges, or direct connections, that a given vertex (node) *v* has with other vertices in the network. In simpler terms, the degree of a vertex indicates how many neighbors, or adjacent vertices, are directly connected to it.

For an undirected graph, where edges have no direction, the degree of a vertex is simply the *count of edges* attached to it. The degree of a vertex is an essential measure because it quantifies the local connectivity of the node, providing insight into its immediate network environment.

Vertex Degree in Graph Theory: In the context of a network (like pedestrian roads), the degree of a vertex (d(v)) represents the number of connections (roads).

High Degree (d(v)): If the vertex degree is high, that means there are more alternative routes. For example, if an intersection is connected to several roads (high degree), people can easily take other paths if one road is under maintenance. Therefore, the *importance of maintenance decreases* since the disruption has less impact.

Low Degree (d(v)): If a vertex has only two connections, it becomes a critical point. If either of those roads is not functional, the remaining option is the only viable route. Hence, the importance of maintenance increases because the impact of a road closure is higher, and there are fewer alternative paths.

2.1.2.3. Betweenness:

In our study, betweenness centrality is a fundamental concept in network analysis that quantifies the importance or centrality of a vertex (or node) within a graph based on *how frequently it acts as a bridge along the shortest paths between other nodes*. It provides a measure of a vertex's *influence* within a network by identifying how often it lies on the critical pathways that connect other nodes. Betweenness describes the extent to which the person is needed as a link in the chains of contacts that facilitate the spread of information in the network. If a person with high betweenness is removed from the network, many flows of information are disrupted or must take longer detours (de Nooy et al. 2005).

In essence, betweenness centrality describes the degree to which a node serves as an intermediary for interactions or flows between other pairs of nodes in the graph. *A high betweenness value indicates that the node is critical for connecting other nodes, making it essential for maintaining the structure or function of the network.[3]*

The centrality of a given vertex in the graph can also be described by a measure based on the number of paths that pass through it – this is the betweenness, b(v), which is defined as the proportion of the shortest paths between every pair of vertices that pass through the given vertex v towards all the shortest paths.[3] More precisely:

$$b(v) = \sum \frac{\sigma_v(s,t)}{\sigma(s,t)}$$

Where:

- s and t are two distinct vertices of G not equal to v.
- σ_v (s, t) is the number of shortest paths from *s* to *t* that pass-through *v* (there can exist several wholly or partially parallel shortest paths from *s* to *t* that have the same length).
- σ (s, t) the total number of shortest paths from s to t.

Vertices with the highest betweenness are those that are located on many shortest paths between other vertices. Girvan and Newman (2003) proposed an equivalent definition of betweenness for edges, the so-called edge-betweenness, which is defined as the proportion of the shortest paths between each pair of vertices that pass through the given edge towards all the shortest paths. The edge-betweenness of a graph G corresponds to the betweenness of its line graph L(G).[3]

Importance of Betweenness Centrality

Betweenness centrality is a powerful metric because it not only captures the direct connections a node has but also the extent to which it controls or facilitates interactions between other nodes. Vertices with high betweenness centrality are often critical for communication or flow within the network, as they act as key connectors or brokers between different parts of the graph. These nodes can be crucial for ensuring the integrity of the network, and their removal or failure could cause significant disruptions in the flow of information or services within the network. Betweenness is a centrality measure in network analysis, which quantifies the importance of a node (or edge) within a network in terms of how often it appears on the shortest paths between other nodes. The betweenness centrality of a node measures the number of shortest paths between other nodes in the network that pass through that node. If a node has high betweenness, it means that it plays a critical role in connecting different parts of the network. [3]

Betweenness = 0:

- If a node has a betweenness centrality of 0, it means **none of the shortest paths between other nodes pass through this node**.
- In terms of a pedestrian network, if a street or pathway has a betweenness of 0, it implies that the path is **not essential** for connectivity. It might be peripheral or less used in terms of linking other important paths.

Betweenness = 0.5 suggests that the node plays a significant but not dominant role in connecting other nodes.

- In a pedestrian network, a path with a betweenness of 0.5 is moderately important.

About half of the shortest paths in the network rely on it, but there are other routes that do not pass through this node.

- It indicates that the node acts as an important connector but is not a total bottleneck. If it were removed or disrupted, the network would be impacted, but not completely crippled, since alternative routes exist.

Betweenness = 1:

- If a node has a betweenness centrality of 1, it indicates that *all shortest paths in the network pass through this node.*
- In a pedestrian road maintenance project, a pathway with a betweenness of 1 would be extremely critical, as it acts as a central hub or bridge that all or most pedestrians must traverse to reach different parts of the network.

High Betweenness and Its Importance:

High betweenness is indeed critical for a project because it indicates that the node (or pathway) acts as a bottleneck or critical connector. If this node were to fail or deteriorate, it could significantly affect the entire network flow rate.

- ✓ For example, if a highly connected pedestrian path (with high betweenness) is under maintenance or blocked, it would force pedestrians to take much longer detours, which could reduce network efficiency.
- ✓ In a maintenance strategy, such pathways with high betweenness would likely need more attention since any issues here would have widespread effects on overall pedestrian flow.

2.1.2.4. Cut Vertex:

A cut vertex, also known as an articulation vertex, is a crucial node in a graph whose removal results in the disconnection of previously connected components. More precisely, a vertex v in a connected graph G is considered a cut vertex if, after removing *v* and all its associated edges, the graph becomes disconnected [4]

The presence of a cut vertex signifies that the vertex plays a critical role in maintaining the overall connectivity of the graph. When such a vertex is removed, the graph may split into two or more disjoint subgraphs, each of which was previously connected through the cut vertex. In this sense, the cut vertex acts as a bridge or bottleneck that facilitates connections between different parts of the graph.[4]

Importance of Cut Vertices

The identification of cut vertices is particularly important in various applications, such as:

- **Network reliability**: In communication or transportation networks, cut vertices are critical points whose failure could disrupt the flow of information or traffic. Ensuring the robustness of these nodes is essential to prevent large-scale disconnection.
- **Social networks**: In social networks, a person represented by a cut vertex might be the only individual connecting two otherwise separate groups. Removing this person from the network could lead to the isolation of these groups.

The identification of cut vertices is also key in network analysis, graph traversal algorithms, and various optimization problems where maintaining connectivity is important.

An example of the cut vertex is shown in Figure 3 (colored in black). If this vertex is deleted, the graph in Figure 3 falls apart into two pieces.[4]

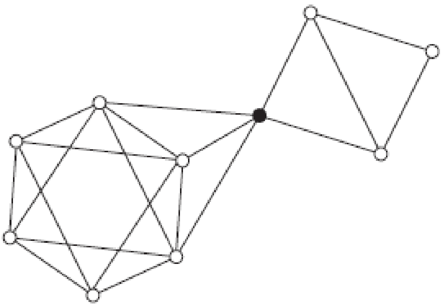


Figure 2: Cut vertex (shown in black) separates the line graph into two biconnected components.

A set of vertices whose removal turns a connected graph G into an unconnected graph is a cut (or a vertex cut). Vertex connectivity κ (G) of the graph G is the size of the smallest vertex cut. Vertex connectivity is usually referred to as simply connectivity. A graph is k-connected if its connectivity is greater than or equal to k. [4]

Similar definitions can be made for the edges of a graph. An edge is a bridge if its deletion increases the number of connected components in a graph. An edge cut of a graph G is a set of edges whose removal causes the graph to become disconnected.

The edge-connectivity κ ′(G) is the size of the smallest edge cut and the graph is k-edge-connected if its edge connectivity is larger or equal to k. Edge-connectivity of a graph G corresponds to (vertex) connectivity of its line graph L(G): κ ′(G) = κ (L(G)). [5]

Vertices *u* and *v* are biconnected if they are connected by two paths that do not share any common internal vertex (i.e. two independent paths). If every two vertices of a graph are biconnected, then the graph is biconnected. Such a graph has κ (G) = 2. Every connected graph has a unique decomposition into biconnected components, which form a tree structure. [6]

In the context of pedestrian road networks, a cut vertex represents a critical point where, if the road connected to this vertex is disrupted, certain areas become inaccessible.

Identifying cut vertices is important for prioritizing maintenance in key areas that could otherwise cause significant disruption.

Calculate Cut-Vertices:

One common method to identify cut vertices is based on *Depth First Search (DFS)* in graph traversal. The following steps outline how cut vertices can be found using DFS:[7]

Algorithm:

The algorithm involves performing a DFS on the graph while maintaining the following information for each vertex:

- **Discovery Time (disc[u])**: The time when a vertex *u* is first visited during DFS.
- **Low Time (low[u])**: The lowest discovery time reachable from the subtree rooted at *u*.

$$\text{if } low[v] \geq disc[u], \text{ then u is a cut-vertex}$$

Conditions for a Cut-Vertex:

- A vertex *u* is a cut-vertex if it is the **root of the DFS tree** and has more than one child.
- A non-root vertex *u* is a cut vertex if there exists a child *v* such that **no vertex in the subtree rooted at v has a back edge to one of the ancestors of u**

Implement the Algorithm:

- Perform a DFS on the graph, tracking *disc[u]* and *low[u]* for each vertex *u*.
- For each vertex *u* and its adjacent vertices *v*, update *low[u]* as:

$$low[u] = \min(low[u], low[v])$$

- Identify cut-vertices based on the conditions mentioned above.

This step implemented in Python directly uses the function **networkx.articulation_points()** to find cut-vertices in a graph.

Table 1 defined the relation between cut vertex and their importance score in our project.

Type of node

Table 1: Rating Scale Cut-Vertex

Cut vertex	1
Non-Cut Vertex	0

2.1.2. QGIS

QGIS (Quantum Geographic Information System) is an open-source geographic information system (GIS) that enables users to create, visualize, analyze, and interpret spatial data. As a powerful tool for geospatial analysis, it is widely used in academic research, urban planning, environmental science, and other fields that require spatial data analysis and mapping. QGIS provides an intuitive interface for handling both vector and raster data, and it supports numerous file formats and databases.

Key Features of QGIS

1. **User-Friendly Interface**: QGIS offers a well-structured interface that allows users, even beginners, to easily navigate and use its features for mapping and spatial analysis.
2. **Support for Multiple File Formats**: It supports various geospatial data formats such as Shapefile, GeoJSON, KML, and spatial databases like PostGIS.
3. **Extensive Plugin Support**: QGIS has a rich library of plugins that extend its functionality. For example, the Network Analysis and Heatmap plugins allow users to perform complex spatial analyses, such as finding critical locations or modeling pedestrian flows.
4. **Open-Source and Community-Driven**: QGIS is freely available, and its development is supported by an active community of developers and users, which ensures constant updates and innovations.

Advantages of QGIS for my Thesis

In our research on pedestrian networks and critical buildings, QGIS proves to be an invaluable tool for several reasons:

- **Spatial Analysis of Pedestrian Networks**: With QGIS, you can analyze pedestrian pathways, intersections, and overall network connectivity. The software enables you to overlay various data layers, such as building locations, and road networks to assess the accessibility and efficiency of the pedestrian network.
- **Identification of Critical Buildings**: By using QGIS's spatial analysis tools, such as proximity and buffer analysis, you can determine which buildings are critical based on their location relative to pedestrian flows, transportation hubs, or emergency services.

QGIS Plugins:

QGIS has several plugins that allow us to download spatial data directly from the website. For example:

- **QuickOSM**: Allows users to download data from “OpenStreetMap” based on queries such specific building types or roads.

2.1.2.1. Quantitative evaluation of sub-criteria in QGIS

In this section we explain the procedure of inserting data into the QGIS and the perform the necessary analysis to *count* the *number* of Critical buildings for each alternative. The steps are as below:

2.1.2.2. Importing Genoa Map:

First, we need to import city map which we are working on, follow the path according to figure 3 & 4.

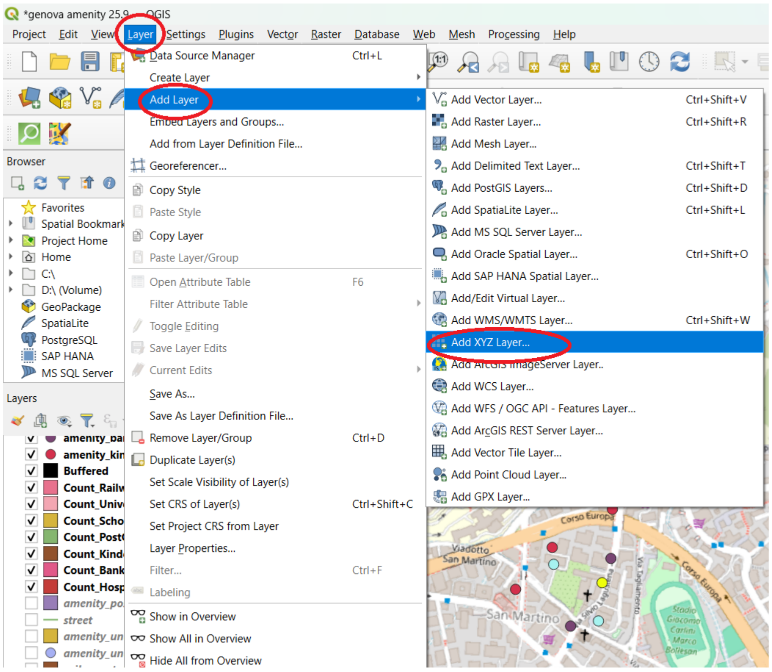


Figure 3: Import City Map to QGIS

By clicking “add XYZ layer”, below window will appear to define data source, we want to use data from “openstreemap” website, then we choose and “Add”.

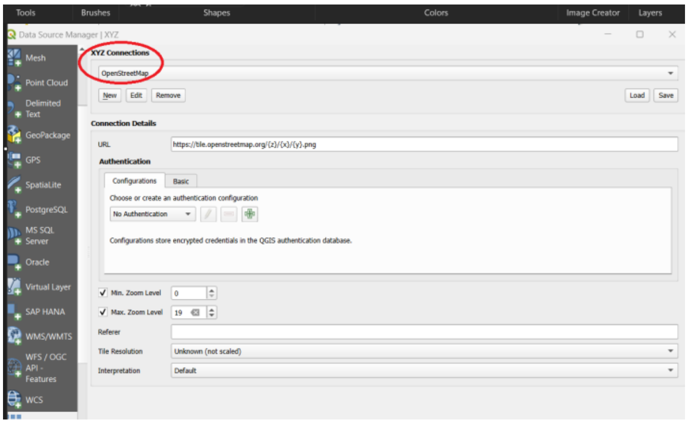


Figure 4: Define data source for importing city map

2.1.2.3. Importing critical buildings:

Follow the path: tap Vector > QuickOSM > QuickOSM and open the following window:

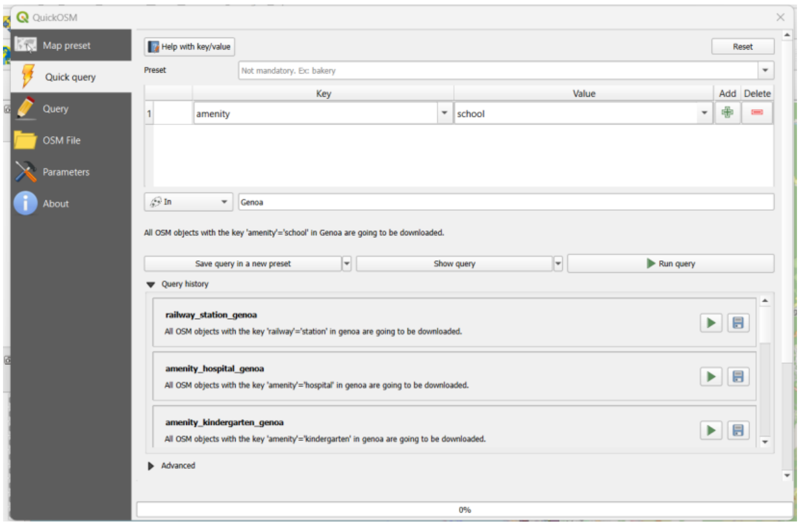


Figure 5: QGIS, Quich query, importing data

Write “amenity” in **Key** field and chose the desire critical building as its **value**, exp. “school”, then choose location, for this study we choose “Genoa”, press “Run Query”. As the result all the data related to the schools in Genoa will be added to the layer panel. For the rest of critical building, we do the same procedure.

After importing all the data, the map is looks like as presented in figure 6.

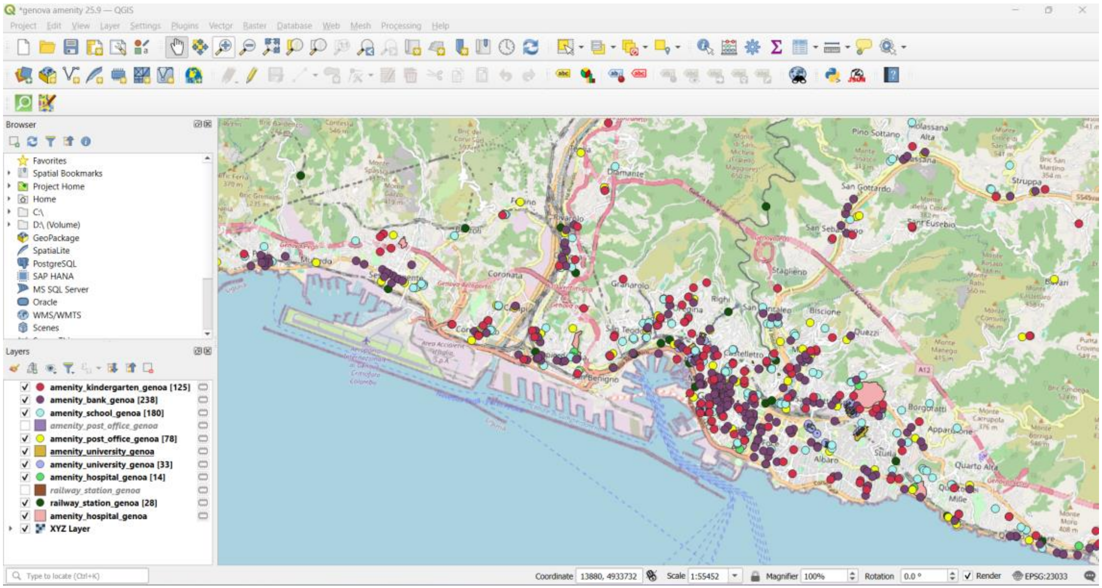


Figure 6: QGIS, Genoa, Defined amenities (critical Buildings), divided by color

Specifying selected street (Alternatives):

For this purpose, we need to create a specific layer and assign all alternatives. We named that layer, “Street” and define only one field “ID” to assign alternative’s label.

Follow path: Layer > create layer > NewGeoPackLayer to open the below window (figure 7). The geometry type, project CRS, and field list set according below.

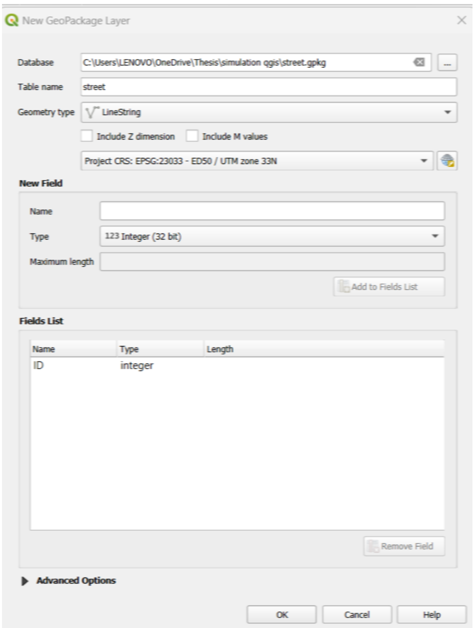


Figure 7: Create layer for identifying alternative’s specifications

Now we should introduce selected streets (alternatives) to this layer, take “Via Pisa” as an example. First, right click on defined layer “street” and enable “Toggle Editing” as figure 8.

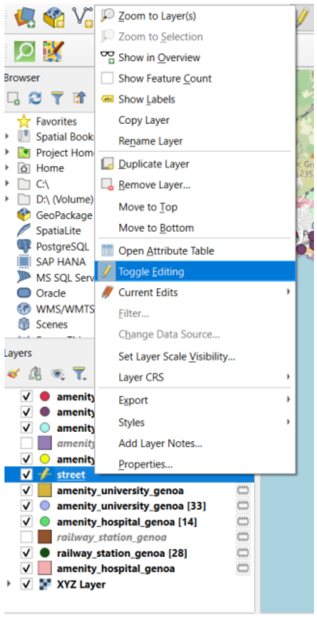


Figure 8: Defining alternatives to QGIS

By activating “Toggle Editing”, select “add line feature” in the toolbar (figure 9) and draw (Drag & Drup) a *line* exactly on Via Pisa, then right click on the map, put ID= 3 (according to alternative Label number defined in next chapter), as figure 10.

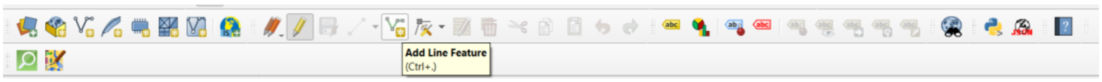


Figure 9: “Toggle Editing” toolbar

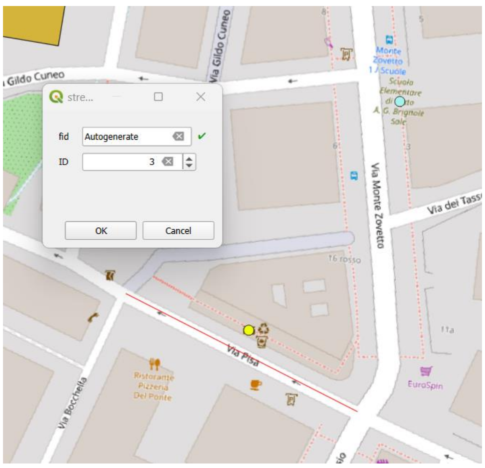
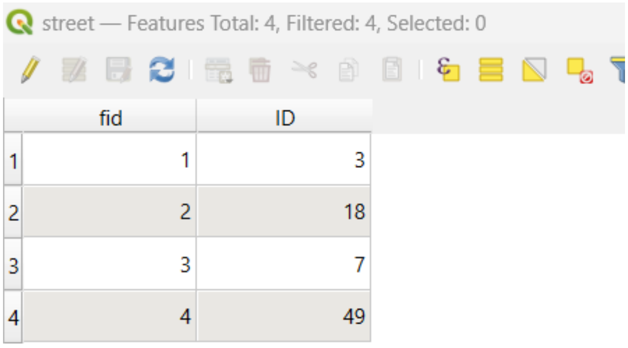


Figure 10: Import Via Pisa to QGIS with ID=3

We do the same for the rest of alternatives (figure 11) and saving the layer “street” by re-clicking on “toggle editing”.



	fid	ID
1	1	3
2	2	18
3	3	7
4	4	49

Figure 11:Import alternatives in QGIS

Create Buffer:

Now, we want to know *how many critical buildings* exist within radius 20 meters of our alternatives, for this purpose, we create a buffer with radius 20m and count number of critical buildings inside it.

Follow path: vector > Geoprocessing Tools > Buffer and open the below window (figure 11):

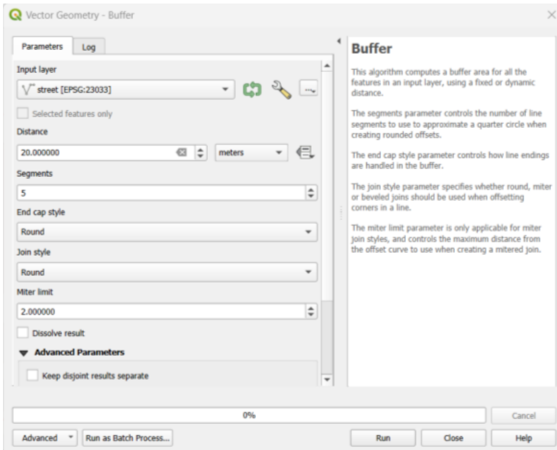


Figure 12: Create Buffer

Choose “**street**” as input layer, then put desire distance (**20 meter)** and click Run to generate Buffer layer as below (figure 12)

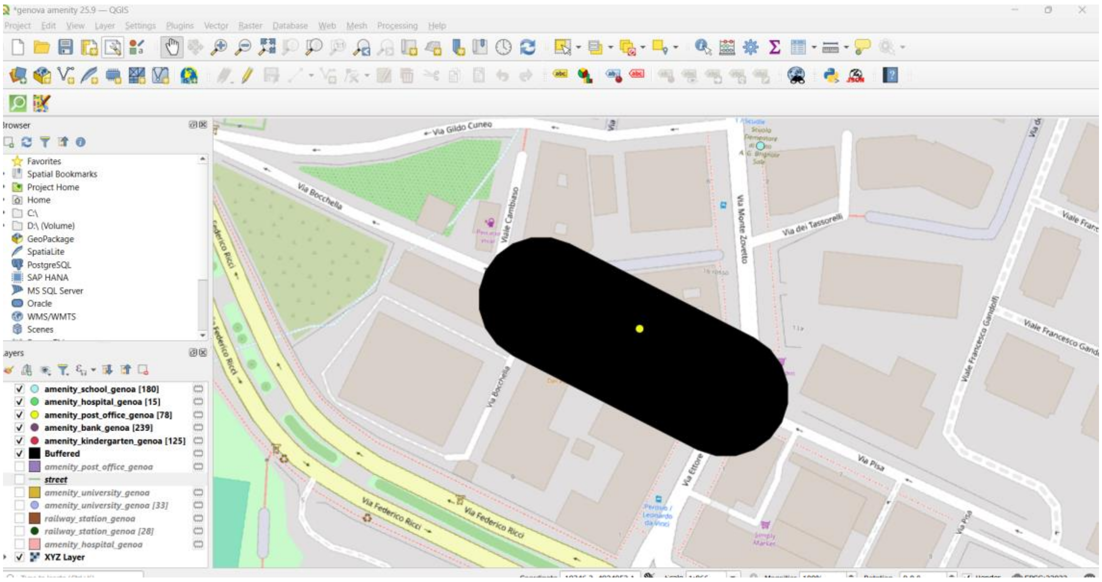


Figure 13: Defined buffer layer for Via Pisa with radius 20 m

Counting critical building:

Follow path: vector > analysis tools > count point in polygon, to perform analysis as below window (figure 13):

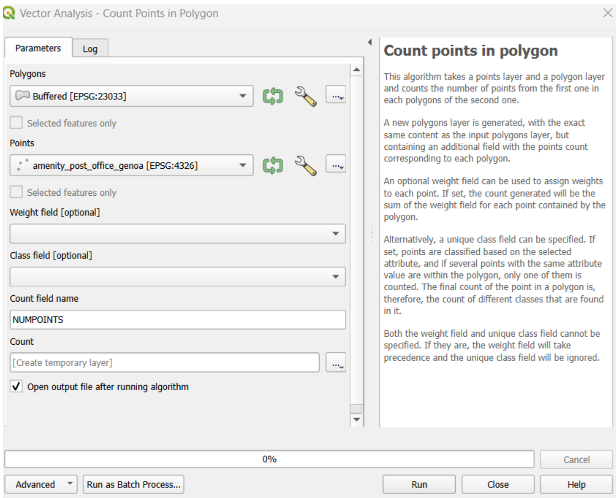


Figure 14: Setting for counting critical building

We want to know how many post offices are located within 20meter radius in our alternatives. As shown in Figure 14, we choose **Buffered** for *Polygons* field (it means, we want to consider our created buffer area), then choose **amenity_post_office_genoa** in *points* field (we want to count the number of post offices), then press Run to create layer *"count" in* layer panel. By right click on count layer, we will find the number of post offices near each alternative.

We do the same for the rest of the alternatives. The result is shown in chapter 3 (figure 29).

Importance Score:

Although all critical buildings are important and need more attention because of frequency in population accessibility but some of them are strongly critical and it is necessary to remove the obstacles to reach them immediately, then we categorized such buildings in table 2.

Definition	Importance Score
Non-Critical Building	1
Post Office/Bank	2
School/ University	3
Park	4
Hospital / Kindergarten/ Train station	5

Table 2: Rating Scale, Critical Buildings

2.1.3. Vulnerable population

Vulnerable populations are groups of people who because of reasons such as age, disability, health condition, or environmental exposure, more susceptible to illness or other social ills. Moreover, by reason of not having access to several basic services, resources, and opportunities, they are excluded from mainstream society. These acts constitute some of the factors that increase the likelihood of damage during times of crisis or performances of everyday life. This is a crucial aspect of a pedestrian network since it directly affects the accessibility, safety, and overall functionality of the network. Vulnerable Population understanding and management are fundamental for urban planning, transportation engineering, and the design of public spaces to ensure that the infrastructure is suitable to their needs. Providing safe walkways for pedestrians is the way to decrease vulnerable populations' risks.

Generally, two major segments of the population are considered to be vulnerable: children under the age of 10 and adults over the age of 70. These age groups are identified to be systemically vulnerable populations when their normal developmental and physiological stages make them more vulnerable to physical, social, and environmental demands.

In this project, we calculate Vulnerable Populations according to **available data which are provided by the municipality of Genoa.** These data are divided by the number of residents separated by zones and ages.

$$VP = \ population\ under\ 10 + population\ more\ than\ 70$$

2.2. Section 2: Ranking Alternatives by Multi-Criteria Decision-Making Analysis

Multi-Criteria Decision Analysis has seen an incredible amount of use over the last several decades. Its role in different application areas has increased significantly, especially as new methods develop, and as old methods improve.

MCDM is an inseparable part of modern decision science. It does this by proposing to support a decision-maker who must deal with a number of criteria and alternatives, recognizing that many problems existing in the real world require several factors to be considered. These developments with respect to MCDM methods have evolved due to the need to address such complexity.

The impact of the MCDM paradigm in business, engineering, and science could be gauged by going through different articles and studies published by Wiecek et al. in 2008. The MCDM enables the simplification of decisions by allowing for a trade-off between the opposite criteria [3].

First, the chapter will outline the necessity of using MCDM in pedestrian road projects, its benefits, why we choose family of ELECTRE methods, and how ELECTRE IV is the most adapted method to this research.

MCDM represents a collection of methods that can be utilized in evaluating and ranking alternatives for decision problems presenting multiple, usually conflicting criteria. In a complicated decision-making environment, MCDM provides a structured approach to analyzing alternatives considering various attributes which are otherwise quite hard to compare. In transportation, MCDM becomes critical for making decisions which often involve integral cost factors, safety, environmental impact, in a justifiable, comprehensive, and transparent manner. Road projects are complex, especially those regarding infrastructure maintenance, with a variety of stakeholders. Each group may have priorities-for instance, municipalities may be interested in budgetary constraints, while local communities emphasize connectivity and safety. MCDM provides, in these contexts, the opportunity for evaluate various kinds of opinions that guide decision-makers to solutions balancing technical and social-economic aspects without relying on a single criterion, such as cost.

Undoubtedly, one of the strong points in using MCDM in road projects involves their handling of qualitative as well as quantitative data. This already reinforces decision-making under uncertainty: such a model would support the consideration of conflicting objectives and avoid the dominance of one criterion. This is particularly relevant when infrastructure maintenance projects, such as pedestrian road maintenance, have all relevant factors important but hardly comparable directly. MCDM methods are designed to cope with such demands by ranking and comparing alternatives based on some criteria, rather than sticking to the quest for one optimal solution.[10]

2.2.1. Selecting Decision Making Method:

- AHP is “a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales” (Saaty, 2008, p. 83). It is one of the more popular methods of MCDM. One of its advantages is its simplicity of use. Its use of pairwise comparisons can allow decision makers to weight coefficients and compare alternatives with relative ease. It is scalable and can easily adjust in size to accommodate decision making problems due to its hierarchical structure. The method has experienced problems of interdependence between criteria and alternatives.[11] Due to the approach of pairwise comparisons, it can also be subject to inconsistencies in judgment and ranking criteria and it “does not allow [individuals] to grade one instrument in isolation, but in comparison with the rest, without identifying weaknesses and strengths” (Konidari and Mavrakis, 2007, p. 6238). Due to the nature of comparisons for rankings, the addition of alternatives at the end of the process could cause the final rankings to flip or reverse. AHP has seen much use in performance-type problems, resource management, corporate policy and strategy, public policy, political strategy, and planning. AHP’s ability to handle larger problems makes it ideal to handle problems that compare performance among alternatives. AHP is unsuccessful when applied to vaguely or ambiguous portrayed real-world problems that involve subjectivity and uncertainty (Efstathiou, 1984; Deng, 1999). the definition of "uncertain" means "not known or decided for sure; open to doubt or questioning." (Khalif, 2016) provided the following definition of uncertainty for use in the context of multi-criteria decision-making applications: "The presence of uncertainty implies that in a given circumstance a person does not possess the quantitative and qualitative information necessary to describe, prescribe, or anticipate the behavior of a system or another characteristic in a deterministic and numerical manner. " Uncertainty can be divided into two types, according to (Durbach and Stewart, 2012).
- ELECTRE (ELimination Et Choix Traduisant la REalité - ELimination and Choice Expressing the REality) along with its many iterations, is an *outranking method* based on concordance analysis. Its major advantage is that it takes into account *uncertainty* and *vagueness*. Further, due to the way preferences are combined, the lowest performances under certain criteria are not displayed.[11] The outranking method causes the strengths and weaknesses of the alternatives to *not be directly identified*, nor results and impacts to be verified (Konidari and Mavrakis, 2007, p. 6237).

  Roy and Bouyssou (1983) proposed ELECTRE IV to simplify the procedure of ELECTRE III. The basic difference between ELECTRE III and ELECTRE IV is that ELECTRE IV does not introduce any weight expressing the weights of the criteria, *which may be hard to measure in practice*. However, this does not mean that the weights of the criteria are assumed to be equal.

Aspect	AHP	Electere
Approach	Hierarchical pairwise comparison	Outranking and pairwise comparison
Criteria Weighting	Explicit (weights must be assigned)	Not always needed (depending on version)
Comparison Type	Quantitative (numerical)	Qualitative (concordance/discordance)
Consistency Check	Consistency Ratio (CR)	No explicit consistency measure
Handling Uncertainty	Less flexible for uncertainty	More flexible (can handle imprecision)
Suitability	When precise weights and rankings are known	When rankings are unclear, or criteria are difficult to weigh

Table 3: Comparison of AHP and ELECTRE [12]

As we see in the above table, and by taking account into our data exported from the website, also there is no weight for our criteria, so we choose the ELECTRE model for decision-making situations.

In our case, we are looking at pedestrian road maintenance strategy, choosing ELECTRE is an appropriate method since it can deal with the problem of lack of specific weights for criteria, which is our decision-making requirement in situations where explicit preferences may not be fully defined and remain ambiguous. Also, the data that we used in this project is subjected to uncertainty, for example: vulnerable people are changeable every year, and data extracted from websites fall under uncertain criteria. Then, choosing the ELECTRE family would be the option.

After choosing the method, it's important to decide about the version of the ELECTRE method, ELECTRE is a family of models, with variants that have been created for different kinds of decision-making situations. The simplest is ELECTRE I, mainly used for binary decision problems in which alternatives are accepted or rejected according to their ability to meet criteria. ELECTRE II introduces a ranking of the alternatives according to their relative strengths and weaknesses with respect to the criteria. ELECTRE III uses pseudo-criteria, building in indifference, preference, and veto thresholds, hence giving a much more flexible way of handling practical data in which uncertainty and imprecision are a common occurrence. ELECTRE IV *does not require weights* and is more appropriate when the *weightings of criteria are only known imprecisely*. This is necessary in road projects, such as the maintenance of pedestrian roads, which involves varying important levels across different criteria such as cost, connectivity, and vulnerability.[13]

This research uses *ELECTRE IV method as decision-making model*, because of the *flexibility* in treating qualitative and quantitative data.

2.2.2 *Ranking of alternatives*

ELECTRE IV step by step, incorporating our sub-criteria and importance scores:

Step 1: Create the Evaluation Matrix:

We create evaluation matrix X with dimensions m × n, which means it has *m* alternatives (A_1; A_2; ….; A_m) and *n* criteria (C_1; C_2; …. ; C_m), then array x_{ij} is the score of alternative A_i in criterion C_j and W_j is the weight of C_j.

	Criteria			
	C_1	C_2	...	C_n
Alternatives	$(w_1$	w_2	...	$w_n)$
A_1	a_{11}	a_{12}	...	a_{1n}
A_2	a_{21}	a_{22}	...	a_{2n}
	.	.	.	
	.	.		.
	.	.		.
A_m	a_{m1}	a_{m2}	...	a_{mn}

Figure 15: performance matrix [2]

Step 2: Normalize & Directionality the data:

In the evaluation matrix, the a_{ij} element (attribute) represents the measure of compliance of the i^{th} alternative to the j^{th} criterion. In order for cardinal measures to be comparable, we must standardize evaluation matrix, so that each measure is between 0 and 1.

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}$$

where x_{ij} is the *value of alternative* i for criterion j, and *n* is the *total number of alternatives*.

handling directionality means, ensure that the **direction** for each criterion is consistent, we have positive valence (e.g. reliability) and negative valence (e.g. costs or consumption) in our criteria, then we need to ensure that the comparison of alternatives reflects whether a high or low value is preferred and maintain consistency in the evaluation process protected. This step done by below formula:

$$\hat{e}_{ij} = \begin{cases} e_{ij}\,, & positive\ criteria \\ 1 - e_{ij}, & negative\ criteria \end{cases}$$

Step 3: Assign Weighs to Criteria [14]:

The entropy weight method (EWM) is an important information weight model that has been extensively studied and practiced. Compared with various subjective weighting models, the biggest advantage of the EWM is the avoidance of the interference of human factors on the weight of indicators, thus enhancing the objectivity of the comprehensive evaluation results. therefore, the EWM has been widely used in decision-making in recent years. The EWM evaluates value by measuring the degree of differentiation. the higher the degree of dispersion of the measured value, the higher the degree of differentiation of the index, and more information can be derived. Moreover, higher weight should be given to the index, and vice versa. The calculation method is as below:

- In the EWM, the entropy value Ei of the i^{th} index is defined as [14]:

$$E_i = \frac{\sum_{j=1}^{n} p_{ij} * \ln{(p_{ij})}}{\ln n}$$

The larger the E_i is, the greater the differentiation degree of index i is, and more information can be derived. Hence, higher weight should begiven to the index.

Finally, the calculation method of weight w_i is [14]:

$$w_i = \frac{1 - E_i}{\sum_{i=1}^{m}(1 - E_i)}$$

Where *m* is the number of criteria.

Step 4: Concordance coefficient [15-17]:

The concordance index between two alternatives A_i and A_j is the sum of the weights for all criteria where A_i performs at least as well as A_j .

C (A_i, A_j) as the concordance index for alternatives A_i and A_j is:

$$\mathrm{C}(A_i, A_j) = \frac{\sum_{k=1}^{m} w_k \delta_k(A_i, A_j)}{\sum_{k=1}^{m} w_k}$$

Where:

w_k is the weight assigned to criterion k (the sum of all weights should be 1).

$\delta_k(A_i, A_j)$ is a binary indicator function:

$$\delta_k(A_i, A_j) = \begin{cases} 1 \ , if\ A_i \geq A_j\ for\ criterion\ k \\ 0\ , \qquad\qquad otherwise \end{cases}$$

This means if alternative A_i performs better than or equal to alternative A_j for criterion k, we add the weight of that criterion to the Concordance index C_{ij}

Step 5: Discordance coefficient [15-17]:

The **Discordance Index** D (**A_i, A_j**) for alternatives A_i and A_j is computed based on how much A_i is worse than A_j in each criterion.

$$D(A_i, A_j) = \frac{Max_k(A_j^k - A_i^k)}{Max_k(A_{max}^k - A_{min}^k)}$$

Where:

- A_j^k and A_i^k are the values of alternatives A_j and A_i for criterion k.
- A_{max}^k and A_{min}^k are the maximum and minimum values for criterion k.

Special Case with Equal Numbers:

- If the values for a criterion are equal, for concordance, you can count that as satisfied (i.e., assign the full weight).
- For discordance, if values are equal, assign 0 since there's no difference.

Step 6: Set Concordance and Discordance Thresholds & Dominance Matrix [15-17]

We define threshold values to determine if one alternative can be considered **better** than another based on the concordance and discordance matrices.

- **Concordance Threshold (c*)**: This threshold represents the *minimum level* of agreement (concordance) needed for one alternative to dominate another.
- **Discordance Threshold (d*)**: This threshold represents the *maximum* level of disagreement (discordance) allowed for one alternative to dominate another.

In this study we set the thresholds *based on the distribution* of the concordance and discordance values; by calculating *mean value* for both matrices, we defined thresholds.

$$Mean = \frac{\sum_{i=1}^{n} x_i}{n}$$

Where:

- x_i is each individual value in the dataset.
- n is the total number of values in the dataset.

Dominance matrix D is a binary matrix where each element D_{ij} indicates whether alternative A_i dominates alternative A_j, and tells us whether one alternative dominates another based on our concordance and discordance thresholds [15-17]

- The concordance index $C_{ij} > c^*$ (i.e., enough agreement).
- The discordance index $D_{ij} \le d^*$ (i.e., not too much disagreement).

The dominance matrix can be computed using the following rule:

$$D_{ij} = \begin{cases} 1 \ , if \ C_{ij} \geq c^* \ and \ D_{ij} \leq d^* \\ 0 \ , \quad otherwise \end{cases}$$

Where:

- C_{ij} is the element from the concordance matrix.
- D_{ij} is the element from the discordance matrix.

Step 7: Rank the Alternative:

- **Count the Number of Dominations (Row-wise Count)**

For each *row* in the dominance matrix, count how many "1"s appear. This tells us how many alternatives each alternative dominates.

- **Count the Number of Times an Alternative is Dominated (Column-wise Count)**

For each *column* in the dominance matrix, count how many "1"s appear. This tells us how many alternatives dominate each alternative.

The priority score for each alternative is calculated by:

P = Row-wise Count - Column-wise Count

Finally, we sorted the indices based on the scores in descending order.

3. Case Study SIMULATION

3.1. The Criteria & Alternatives

After studying the literature, the 6 criteria such as Cost, Vertex Degree, Betweenness, Vulnerable Population, Cut vertex, and Critical Building were defined. Network connectivity, Users and their vulnerability, Cost were identified as the main criteria for this study. The criteria, their symbols, and the approach of each criterion in terms of profit (positive) or cost (negative) are depicted in Table 4.

TABLE 4: Criteria

SYMBOL	CRITERIA	TYPE
$C_{1.1}$	Vertex Degree, d(v)	Cost
$C_{1.2}$	Betweenness, B(v)	Profit
$C_{1.3}$	Cut vertex	Profit
$C_{2.1}$	Critical Building (CB)	Profit
$C_{2.2}$	Vulnerable Population (VP)	Profit
C_3	Cost	Cost

In this study, we choose four streets in 4 different zones in Genoa:

Alternatives	*Name of Zone*	*Label of Link*
A1	Via Roma (Castelletto)	49
A2	Via san Martino (S. Martino)	18
A3	Via Adamo Centurione (S. Teodoro)	7
A4	Via Pisa (Albaro)	3

Table 5: Selected links for the project- Genoa

Alternatives	Link label in graph (G)	Graph (u)	Graph (v)	Node label in L(G)	Line graph (u)	Line graph (v)
A1	49	5631887890	5573738169	7	5573738169	5631887890
A2	18	1489428512	504574847	3	504574847	1489428512
A3	7	880487185	267170259	6	880487185	267170259
A4	3	251687361	144720279	7	144720279	251687361

Table 6: Alternative's attributes in graph and line-graph

Figure 16: Via Roma

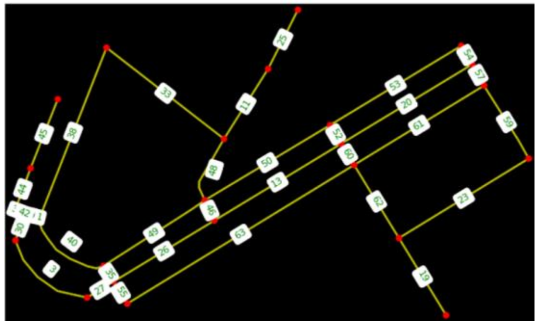


Figure 17: Graph (Link & Node), Via Roma

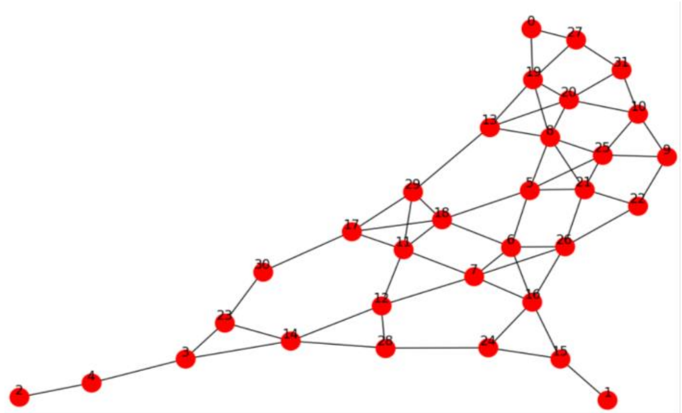


Figure 18: Line-Graph, Via Roma

Figure *19*: Via San Martino

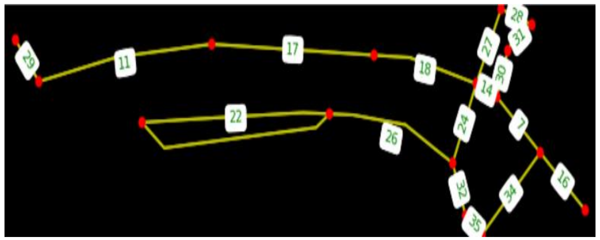


Figure 20: Graph (Link & Node), Via San Martino

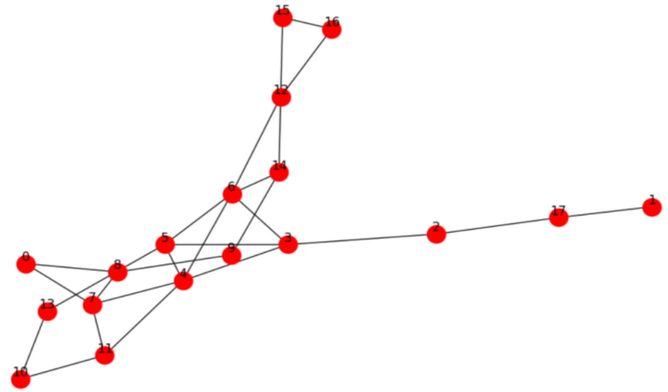


Figure 21: Line-Graph, S.Martino

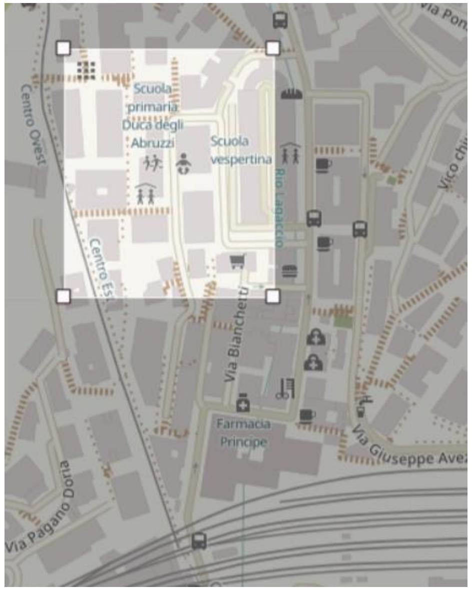


Figure 22: Via Adamo Centurione

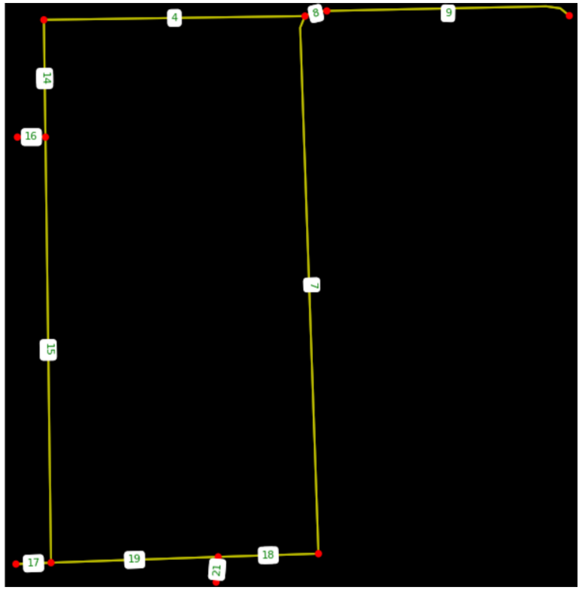


Figure 23: Graph (Link & Node), Via Adamo Centurione

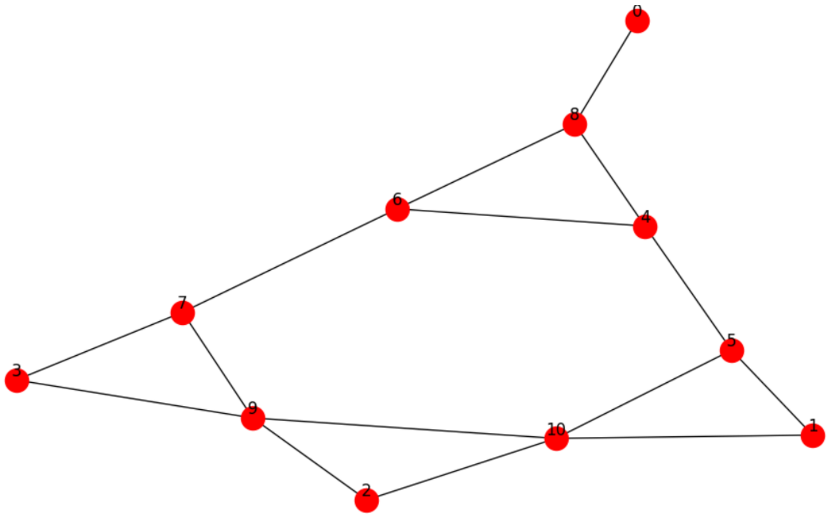


Figure 24: Line-Graph, Via Adamo Centurione

Figure *25*: Via Pisa

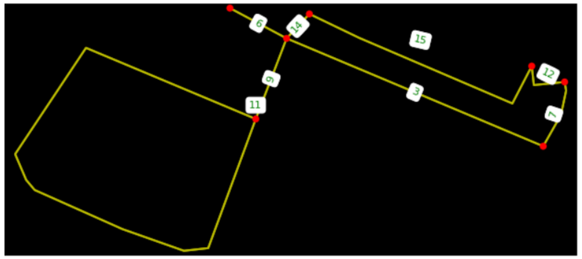


Figure 26: Graph (Link & Node), Via Pisa

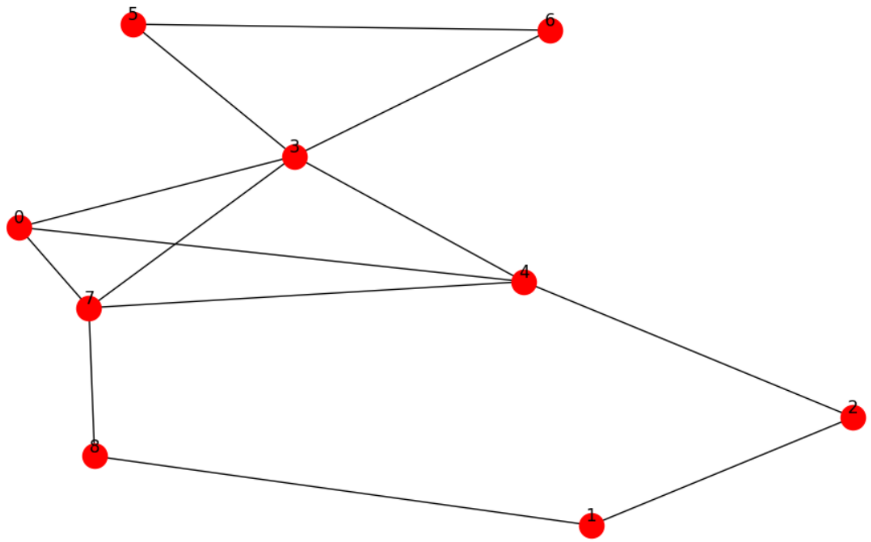


Figure 27: Line-Graph, Via Pisa

3.2. Quantitative evaluation of criteria with Python

Step 1: For creating a pedestrian network (nodes and links) for each area, we extracted boundaries of the desired area from “Open Street Map” website and by using Python codes we transferred the geographical map to the node and link network. (results are, figure16,19, 22, 25)

```
# Define the bounding box coordinates for Genoa, Italy (Piazza Raffaele Rosssetti & Corso Guglielmo Marconi)
north, south, east, west = 44.39687, 44.39575, 8.94704, 8.94498

# Download the street network data from OpenStreetMap for the defined bounding box
graph = ox.graph_from_bbox(north, south, east, west, network_type='walk')
```

```
C:\Users\39320\AppData\Local\Temp\ipykernel_9868\1939025927.py:5: FutureWarning: The `north`, `south`, `east`, and `west` parameters are deprecated and w
ill be removed in the v2.0.0 release. Use the `bbox` parameter instead. See the OSMnx v2 migration guide: https://github.com/gboeing/osmnx/issues/1123
  graph = ox.graph_from_bbox(north, south, east, west, network_type='walk')
```

```
# Iterate over the edges and assign a custom ID to each edge
for i, (u, v, key, data) in enumerate(graph.edges(keys=True, data=True)):
    data['custom_id'] = i

# Print the edges with their custom IDs
for u, v, key, data in graph.edges(keys=True, data=True):
    print(f"Edge: ({u}, {v}, {key}), Custom ID: {data['custom_id']}")

# Prepare edge labels as custom IDs for plotting
edge_labels = {(u, v): data['custom_id'] for u, v, key, data in graph.edges(keys=True, data=True)}

# Plot the graph with custom IDs as edge labels
fig, ax = ox.plot_graph(graph, node_color='r', node_size=30, edge_color='y', edge_linewidth=1.5, bgcolor='k', show=False, close=False)
pos = {node: (data['x'], data['y']) for node, data in graph.nodes(data=True)}
nx.draw_networkx_edge_labels(graph, pos, edge_labels=edge_labels, font_size=8, font_color='green', ax=ax)

# Display the plot
plt.show()
```

Step 2: Since the centrality and topological measures can only be calculated for vertices and not for edges, then we initially translate edges into vertices by generating a line graph. (as described in section 2.1.2)

This step is done by coding in Python and the results are shown in Figures 17, 20, 23, 26

Step 2: Create Line graph

```
20]: # Create the line graph (line graph transformation)
line_graph = nx.line_graph(graph.to_undirected())

# Assign custom IDs to nodes in the line graph
for i, node in enumerate(line_graph.nodes):
    line_graph.nodes[node]['custom_id'] = i

# Draw the line graph with node IDs
plt.figure(figsize=(10, 6))
pos = nx.spring_layout(line_graph, seed=42)  # Using a fixed seed for reproducibility
nx.draw(line_graph, pos, with_labels=False, node_color='r', node_size=300)

# Draw node labels (custom IDs)
node_labels = {node: f"{line_graph.nodes[node]['custom_id']}" for node in line_graph.nodes}
nx.draw_networkx_labels(line_graph, pos, labels=node_labels, font_color='black', font_size=12, verticalalignment='bottom')

# Draw edge labels (if applicable, adjust as needed)
edge_labels = nx.get_edge_attributes(line_graph, 'weight')
nx.draw_networkx_edge_labels(line_graph, pos, edge_labels=edge_labels, font_color='blue', font_size=8)


#Print the nodes with their IDs
for node, data in line_graph.nodes(data=True):
    print(f"Node: {node}, Node ID: {data['custom_id']}")

# Display the plot
plt.title('Line Graph with Node IDs')
plt.tight_layout()
plt.show()
```

Step 3: Centrality and topological measures done by using Python, for example:

```
# Identify cut vertices in the line graph
cut_vertices = list(nx.articulation_points(line_graph))

# Print the cut vertices with their custom IDs
print("Cut vertices (articulation points) in the line graph:")
for node in cut_vertices:
    print(f"Node: {node}, Custom ID: {line_graph.nodes[node]['custom_id']}")

# Draw the line graph with node IDs
plt.figure(figsize=(10, 6))
pos = nx.spring_layout(line_graph, seed=42)  # Using a fixed seed for reproducibility

# Highlight cut vertices in green, others in red
node_colors = ['g' if node in cut_vertices else 'r' for node in line_graph.nodes]
nx.draw(line_graph, pos, with_labels=False, node_color=node_colors, node_size=300)

# Draw node labels (custom IDs)
node_labels = {node: f"{line_graph.nodes[node]['custom_id']}" for node in line_graph.nodes}
nx.draw_networkx_labels(line_graph, pos, labels=node_labels, font_color='black', font_size=12, verticalalignment='bottom')

# Highlight and label cut vertices with their custom IDs
cut_vertex_labels = {node: f"Cut {line_graph.nodes[node]['custom_id']}" for node in cut_vertices}
nx.draw_networkx_labels(line_graph, pos, labels=cut_vertex_labels, font_color='blue', font_size=12, verticalalignment='top')

# Draw edge labels (if applicable, adjust as needed)
edge_labels = nx.get_edge_attributes(line_graph, 'weight')
nx.draw_networkx_edge_labels(line_graph, pos, edge_labels=edge_labels, font_color='blue', font_size=8)

# Print the nodes with their custom IDs
print("\nNodes in the line graph with their custom IDs:")
for node, data in line_graph.nodes(data=True):
    print(f"Node: {node}, Node ID: {data['custom_id']}")
```

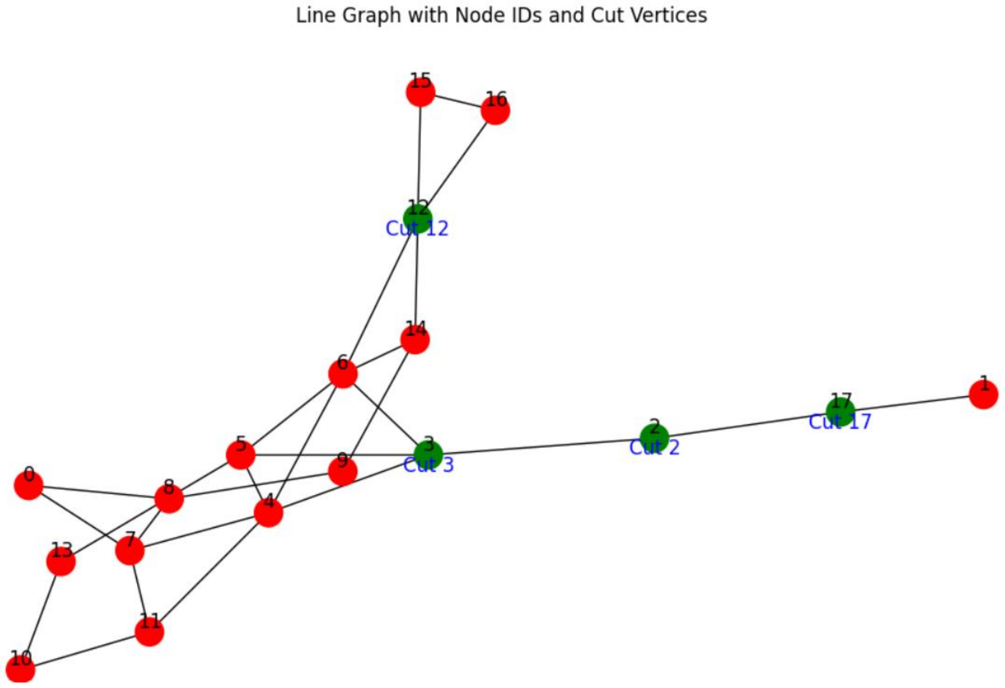


Figure 28: Green nodes are Cut vertex

Critical buildings calculated in QGIS as explained in section 2.1.2.1 and the results are as figure 29.

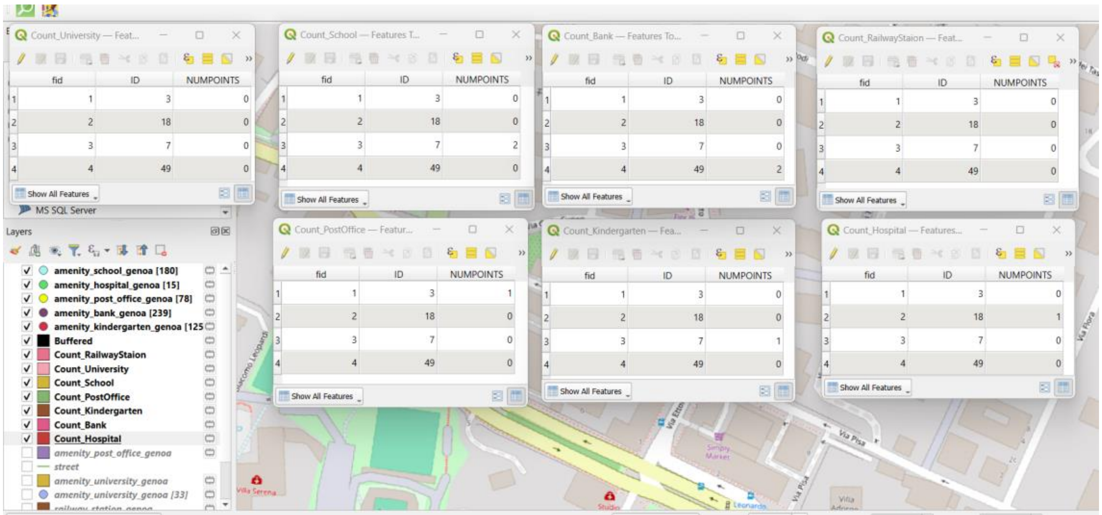


Figure 29: Number of critical buildings in all alternatives using QGIS

Vulnerable information calculated based on data from the municipality of Genoa which include people less than 10 and more than 70 years old.

The overall results are summarized in table 7.

ALTERNATIVE	D(V)	B(V)	CUT VERTEX	CRITICAL B.	VULNERABLE P.	COST
A1	5	0.42	0	2*Banks	3565	650
A2	4	1	1	1*hospital	2688	1320
A3	3	1	0	2*school+1kindegarden	3285	1868
A4	4	0	0	1 * post office	2714	340

Table 7: Alternatives measurement in different criteria

Step 4: **Decision Matrix**: All criteria normalized & Directed (All steps to ranking alternatives done by Python).

ALTERNATIVE	D(V)	B(V)	CUT VERTEX	CRITICAL B.	VULNERABLE P.	COST
A1	0.68	0.17	0	0.18	0.29	0.84
A2	0.75	0.41	1	0.22	0.21	0.68
A3	0.81	0.41	0	0.5	0.26	0.55
A4	0.75	0	0	0.09	0.22	0.91

Table 8: Normalized & Directed data

Step 5: Weighting criteria: According to entropy method:

```
Weights based on Entropy:
                               Weights
D(v)                          0.174560
B(v)                          0.116261
Cut-vertex                    0.457917
Number of Critical Buildings  0.057821
Vulnerable Population         0.002468
Cost                          0.190971
```

Step 6: Concordance Matrix:

```
Concordance Matrix:
          A1       A2        A3        A4
A1  0.000000  0.19344  0.193440  0.176551
A2  0.806560  0.00000  0.648889  0.632000
A3  0.348643  0.23485  0.000000  0.351111
A4  0.365532  0.19344  0.190971  0.000000
```

Step 7: Discordance Matrix:

```
Discordance Matrix:
          A1        A2        A3        A4
A1  0.000000  0.806560  0.348643  0.365532
A2  0.193440  0.000000  0.234850  0.193440
A3  0.193440  0.648889  0.000000  0.190971
A4  0.176551  0.632000  0.351111  0.000000
```

Step 8: Concordance & Discordance thresholds:

SYMBOL	VALUE	DESCRIPTION
C*	0.33	Concordance threshold
D *	0.35	Discordance threshold

Step 9: Dominance Matrix:

```
Dominance Matrix:
     A1   A2   A3   A4
A1  0.0  0.0  0.0  0.0
A2  1.0  0.0  1.0  1.0
A3  1.0  0.0  0.0  1.0
A4  1.0  0.0  0.0  0.0
```

Step 10: Alternatives Ranking:

```
Priority Ranking
[2 3 4 1]
```

CONCLUSIONS

This study presents the successful adoption of a multi-criteria decision-making (MCDM) framework using the ELECTRE IV method for prioritizing pedestrian road maintenance The decision criteria, D(v), B(v), cut-vertex, number of critical buildings, vulnerable population, and cost, were purposefully chosen to deal with network connectivity, vulnerability, and financial constraints that are the major issues of urban infrastructure.

Measuring the entropy method provided for the objective weighting of the criteria, which was fair, and thus the cut-vertex criterion, which is essential for the stable maintenance of a network, was given the highest percentage. The computations of the concordance and discordance matrices, followed by the dominance matrix, resulted in robust *non-compensatory* decision-making for the road segment prioritization based on such principles as no single criterion could have dominated the process.

The results provided a clear maintenance priority ranking, which highlighted the segments that were vital to the network's connectivity and the segments that served vulnerable populations. The flexibility of the methodology enabled it to adapt to varying urban settings or planning goals by the manipulation of the concordance and discordance thresholds.

FUTURE DEVELOPMENTS

While the framework offers a strong tool for maintenance prioritization, the study acknowledges some limitations, such as:

- Static data are used, and the cost estimates are cumbersome to compute. The future of this research could thus consider dynamic data input, such as real-time pedestrian flow or condition monitoring, to further enhance the effectiveness of the approach
- A deeper analysis of the proposed methods could be carried out while considering the discordance of criteria as this could solve some issues found in this work.

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