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A Generic Betweenness Centrality-Based Approach for Urban Street Network Reallocation to Mitigate Climate Change Impacts

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Abstract

Urban areas face escalating climate change impacts, including rising temperatures and extreme weather events, exacerbated by urban heat islands (UHIs) and limited green spaces. With over 4 billion urban residents globally, cities must adapt by reallocating urban land, particularly street networks, which occupy 20–30% of urban surfaces. This study proposes a generic method to address two variants of street network reallocation: (1) maximizing reallocated lanes while minimizing increased travel distances, and (2) relocating congested areas from city centers to peripheral zones. Leveraging edge betweenness centrality (EBC), we develop two algorithms: L-EBC (lowest EBC arcs for space optimization) and H-EBC (highest EBC arcs for traffic redistribution). Applied to approximately 50 real urban street networks extracted from Open Street Map, L-EBC achieves high space reallocation with minimal impact on All-Pairs Shortest Paths (APSP), while H-EBC shifts traffic congestion outward using metrics like $\boldsymbol{M_{center}}$ (centroid displacement) and $\boldsymbol{M_{spread}}$ (spatial dispersion). The work acknowledges city-specific constraints but provides a theoretical foundation for planners to

initiate data-driven reallocation. Future directions include integrating temperature models, satellite data, and urban planner heuristics to refine targeted interventions.

Keywords: Climate Change Mitigation, Urban Street Networks, Graph Model, Edge Betweenness Centrality, Lane Reallocation

1 Introduction

Among the major challenges humanity have to overcome in the coming decades, climate change is undoubtedly among the most critical. The effects of climate change are numerous, these include increased land temperatures, flooding, glacier retreat, sea level rise, increased frequency of extreme weather events, and ecosystem disruptions, to name just a few [1]. Urban environments, in their current configurations, are highly vulnerable to many of these impacts [2], particularly rising temperatures and the phenomenon of commonly known as urban heat islands [2][1]. An aggravating factor is the continued year-on-year growth of the global urban population that now exceeds 4 billion people in some places. This growth is accelerating, with an increase of over 400 million urban residents between 2015 and 2020 alone [3].

Aware of these risks, many metropolitan areas have begun implementing a range of strategies to mitigate the effects of climate change. These include restricting the circulation of highly polluting internal combustion vehicles in city centers (e.g., "Paris Respire" in Paris, "Ultra Low Emission Zone" in London), improving public transportation systems, establishing street networks dedicated to active mobility (e.g., "Ciclovía" in Bogotá), and expanding green spaces. In the 2022 IPCC report, expanding green spaces is explicitly recommended: *"Nature-based strategies, including street trees, green roofs, green walls and other urban vegetation, can reduce heat and extreme heat by cooling private and public spaces (robust evidence, high agreement)"* [2][2]. Implementing some of these strategies, such as creating green spaces or reallocating streets for active mobility, requires repurposing portions of the existing urban fabric. In rare cases, cities possess unused land reserves such as former industrial sites or decommissioned railway lines. Projects like 'City Link' in Melbourne, 'Shibuya Station' in Tokyo, or 'Tempelhofer Feld' in Berlin rely on the availability of outdated buildings or obsolete infrastructure that can be demolished. In the case of Detroit ('Urban Green Space Projects'), numerous buildings were vacated following a significant population decline in the early 2000s. However, in most cases, such reserves do not exist, hence repurposing of land that is already in use become necessary. In practice, urban land serves multiple purposes: residential, commercial, and industrial buildings; green and natural areas; public facilities (e.g., hospitals, schools, universities, administrative buildings); recreational infrastructure (e.g., stadiums, swimming pools); technical infrastructure (e.g., power plants, wastewater treatment plants, incinerators, water

[1] Section 6.2.2.1 'Temperatures and the Urban Heat Island' of the IPCC report.
[2] Section 6.3.4.1 "Temperature Regulation" of the IPCC report.

reservoirs, waste facilities); and the street network. Although it is sometimes possible to reallocate built-up areas to other uses, this option remains limited. In contexts where neither population nor urban activities are shrinking, the land available from reallocated buildings is minimal. Public facilities and technical infrastructure are often already located on the urban fringe or are difficult to relocate.

Among all land uses, the street network reallocation emerges as the one with greatest potential for transformation. Furthermore, while the built environment occupies most urban land, depending on the country, the street network represents the second largest land use, accounting for between 20 and 30% of the total urban surface [4]. As a result, the idea of reallocating part of the street network for alternative uses has naturally become a core component of development strategies in numerous cities and metropolitan areas. Section 2.2 elaborates this in more detail. While each municipality adopts strategies based on local characteristics and specific constraints. It is arguable that a study focusing solely on the topological characteristics of the street network, and more specifically on betweenness centrality value of arcs, can yield insights useful for decision-making.

The main contribution of this work is a generic method for addressing two variants of the central problem of reallocating partially urban street networks. Apart from reallocation of street lanes for recreational purposes on both variants, the first variant can be formulated as a bi-objective optimization problem: maximizing the number of reallocated lanes in the street network while limiting the increase in distances between locations within the city. The second variant attempts to reallocate the street network so that the original congested areas (mostly from city center) are relocated to more peripheral districts where congestion of traffic and street lanes are better compromised.

A common generic method, based on the betweenness centrality measure of the arcs, is proposed for addressing these problems.

The considered urban street network model, along with the formulation of the street reallocation problem and its associated restrictions and constraints, are described in detail in Section 3.

This article is organized as follows. Section 2 begins with a review of studies on topological properties of urban networks and of road space reallocation projects implemented in several cities. It then reviews two main bodies of literature: studies that use betweenness centrality to analyze road networks, and studies that aim to reduce the size of these networks. It is also identifying the shortcomings of existing research in which this work attempts to address. Section 3 presents the modeling of the street network, and the problem formulation, taking into account constraints such as strong connectivity. The methodology, together with the experimental setup, are illustrated in Section 4. Based on the analysis of approximately 50 cities of varying sizes located in different geographical regions, Section 5 demonstrates that the application of the betweenness centrality metric to both variant which can either optimize space utilization while maintaining, on average, similar path lengths, or optimize space while implicitly redistributing traffic flow from the city center to the urban periphery.

Finally, the article is concluded where perspectives, potential applications are discussed, and future directions are suggested.

2 Related Works

2.1 Topological and Structural Properties of Urban Street Networks

Structural properties of urban street networks have been extensively studied during the last decades, using graph-theoretic representations to characterize cities as spatial networks. Early comprehensive comparisons were conducted by [5, 6], where eighteen cities distributed across four continents were analyzed. The work also introduced the Multiple Centrality Assessment (MCA) framework. In these studies, the street network of each city was represented as a *primal* planar graph, where nodes correspond to street intersections and edges to street segments. The networks contained between 2,000 and 10,000 nodes and up to 15,000 edges, encompassing cities ranging from compact medieval cores (e.g. Bologna, Venice) to large modern ones (e.g. New York, Los Angeles).

The metrics considered in these works include both *local* measures, such as degree or clustering coefficient, and *global* ones, such as network diameter, average shortest path or betweenness, closeness, straightness, and information centralities. A key contribution of these analyses was the comparison of the *distributions* of centrality measures across cities, revealing systematic differences between self-organized and planned urban forms. Self-organized networks exhibited broad, often power-law-like distributions of centrality, while planned grid cities displayed more homogeneous patterns.

A related study by [7] extended the comparison to twenty cities worldwide, analyzing structural metrics of planar street graphs such as characteristic path length, diameter, efficiency, and clustering. Their results confirmed that self-organized cities (e.g., Venice, Cairo) tend to be more locally efficient but globally less integrated than planned counterparts (e.g., Manhattan, Brasilia). [8] similarly compared seventeen self-organized and planned settlements emphasizing robustness and degree distribution patterns, further highlighting the topological distinction between the two morphological types.

In 2013, another contribution extended this approach by applying multivariate statistical analysis to the same suite of centrality measures across ten European cities. Rather than reproducing the binary classification of [5] and [6], they demonstrated that urban street networks occupy a continuous spectrum of structural configurations [9]. Using principal component analysis and hierarchical clustering on normalized centrality distributions, they identified three to four recurrent patterns of spatial organization: highly integrated grid-like forms (e.g. Barcelona, Milan), organic or medieval patterns with broad and hierarchical centrality distributions (e.g. Bologna, Catania), mixed or transitional structures (e.g. Paris, Geneva), and polycentric or dispersed layouts (e.g. Edinburgh, Leicester). This analysis showed that differences in the spatial distribution and correlation of centrality values, rather than grid regularity alone, provide a robust quantitative basis for distinguishing urban forms. Hence, Strano *et al.* reframed the

topological classification of cities as a multivariate continuum of integration patterns, refining the earlier dichotomy into a more general typology.

Finally, the work in [10] reviewed the broader field of spatial networks, synthesizing empirical results from dozens of urban studies. Typical city street networks were found to comprise between 1,000 and 30,000 intersections, with small-world characteristics, limited average diameters (20–60), and efficiency levels constrained by planarity.

Overall, the comparative analyses of urban street networks reveal that city topologies form a continuum rather than a strict dichotomy. Earlier studies [5–7] identified two prototypical extremes, these are : First, *self-organized* or organic networks, characterized by heterogeneous degree and centrality distributions, high local clustering, and long global path lengths; Second, the *planned* or grid-like networks, exhibiting more homogeneous centrality patterns, lower clustering, and higher global integration. Subsequent the work in [9] refined this view by showing that cities occupy intermediate positions within a continuous morphological spectrum. Differences in the spatial distribution and correlation of centrality values capture distinct modes of spatial organization. Hence, the typology of urban networks is best understood as a gradation of integration patterns emerging from the combined behavior of centrality distributions, efficiency, and robustness metrics, rather than as a binary opposition between organic and planned forms.

In summary, the most recent literature suggests that urban street networks cannot be classified into any strict or narrowly bounded set of categories. This implies that each network ought to be studied independently, without the need to assign it to any particular structural class.

2.2 Actual Reallocation of Urban Street Space in Cities

Prompted by increasingly alarming reports, particularly those produced by the IPCC, and in the absence of coordinated national and international policies. Around the turn of the 2000s, metropolitan areas and medium-sized cities began to develop projects aimed at mitigating the effects of climate change. Among these initiatives, some explicitly aim to reduce the extent of the urban street network and to reallocate portions of it for alternative uses.

Barcelona has implemented the "Superblock" model to promote green spaces and reduce car traffic within its grid-structured city center [11]. A similar approach can be found in the United States through the "Road Diet" initiative, which aims to reallocate a portion of the road network for bicycle lanes, among other uses [12]. In New York City, Times Square has been transformed into a pedestrian-friendly and cyclist-friendly area. The riverbanks in Paris have been closed to motor vehicles and are now reserved for pedestrians and cyclists only. In the same spirit, Seoul dismantled the elevated Cheonggyecheon Expressway and restored the stream that once flowed beneath it. In São Paulo, the Minhocão elevated highway is converted into a linear park, known as "Parque Minhocão." However, these initiatives are not limited to large metropolitan areas. In Spain, Pontevedra, a city of fewer than 100,000 residents, has comprehensively restructured its street network by establishing car-free zones and restricted access areas [13], leading to a significant reduction in traffic and air pollution. In Belgium, the city of Ghent adopted a circulation plan that reduced car traffic

in the city center to expand green areas and cycling infrastructure. This results in a 25% reduction in central traffic. In Delft, Netherlands, the city has removed parking spaces and car lanes to create urban gardens and green pedestrian corridors. A similar effort was undertaken in the Vauban district of Freiburg, Germany, where many streets were closed to vehicular traffic and, in some case, they were repurposed to improve stormwater management if possible. A comparable concern has guided Malmö's urban policy in Sweden, where parts of the street network had been redesigned to mitigate flood risk by increasing permeable surfaces and implementing vegetated swales. All of these examples reflect not only a growing awareness of the challenges posed by climate change but also a global trend toward implementing policies for the partial reconversion of urban street networks, often were a significant reduction in traffic. However, if common principles for reallocating urban street space exist, each implemented solution remains highly context-dependent and an ad hoc design. Consequently, when considering a graph-based modeling of the urban street network, no universal, metric-driven approach can be directly inferred from existing implementations. Nonetheless, a substantial theoretical literature based on graph analysis has investigated this problem in depth. This research is the first to address the shortcomings of existing approachs by implementing generic graph-based algorithms. Section 3 describes this in detail.

2.3 Betweenness Centrality-based Approaches to Urban Street Network Studies

This work utilizes the concept of 'Betweeness Centrality Value', a well-known measure in graph theory. This measure is used to guide the selection of lanes for reallocation. The detail of the approach is described in Section 3. In this section, its concept and related previous works which adopted this measure is discussed briefly.

Betweenness Centrality (BC) quantifies the likelihood that a node lies on the shortest path between two randomly selected nodes (assuming the equiprobability of all pairs) [14]. The betweenness centrality of a node 'u' is proportional to the sum, over all pairs of vertices (excluding 'u'), of the ratio between the number of shortest paths that pass through 'u' and the total number of shortest paths between those vertices. For a graph $G = (V, E)$:

$$BC_u = \frac{1}{(n-1)(n-2)} \sum_{v,w \in V} \frac{SP^u_{v,w}}{SP_{v,w}}$$

Where $|V| = n$ and $SP_{v,w}$ denotes the number of shortest paths between nodes v and w, and $SP^u_{v,w}$ is the number of shortest paths between v and w that pass through 'u'. This measure is also commonly known as, the Edge-Betweenness Centrality (EBC).

In their seminal work on graph modeling of urban streets, Porta and his colleagues [5] used four different centrality measures, noting that the concept of centrality can be understood in different ways. While closeness conveys the idea of "being near the others", betweenness reflects the notion of being on the way to the others, or, "being between the others" [5]. Among the two interpretations, being near is preferable and relevant one as since streets serve as the medium for mobility.

In an urban context, BC and EBC have been widely used to classify streets, assess their structural importance within the network, and estimate traffic flows. The study in

[6], suggested that BC is "able to identify the primary structure of movement channels as different from that of secondary, local routes." A similar study [15], proposed a visualization method based on the computation of local betweenness centrality (or k-betweenness centrality [16]), allowing a clear distinction between streets used for long-distance travel and those used by pedestrians. Although the term was not mentioned, BC was also considered in the work of Hillier and his colleagues [17]: "a similar measure is 'global choice', which indexes how often each line is used on topologically shortest paths for all lines to all other lines in the system". One secondary outcome of their pioneering study is that "people move by the shortest possible route", thus highlighting the relation between BC and traffic flows when considering pedestrian movements. In 2008, Jiang and his colleagues [18] showed that urban street networks exhibit a hierarchical organization in which a small proportion of streets carries the majority of the traffic flow. This observation supports the idea that identifying a limited subset of structurally important streets, such as those with high edge betweenness centrality, may be sufficient to characterize the backbone of the network. Kazerani and Winter [19] showed that betweenness centrality partially explains traffic flow patterns in urban networks, but also highlight discrepancies between topological centrality and observed movements. The approach in this work leverages EBC not as a predictive model of traffic, but as a design metric to actively reshape the spatial distribution of central routes in the network. Based on the assumption of a close relation between BC and traffic. In classification of streets in cities, Valença and his colleagues [20] used BC values for estimating the position of a street into such a hierarchy: the higher the BC value, the higher the street in the hierarchy. The work is closely related to the approach taken in this work, as both rely on graph-theoretic measures to characterize the structural importance of streets in urban networks. However, while both focus on identifying where reallocation is difficult, this work utilizes EBC to actively guide the redistribution of street functions and reconfigure the spatial structure of the network.

2.4 Graph-based Approaches to Urban Street Network Reallocation

While respect to street reallocation, recent research has explored graph-based methods to reallocate urban street networks too. Notable contributions include the works of [21] and [22]. The main objective of [21] is to reallocate part of the existing road space to bicycles while considering public transport systems and other urban constraints, such as residential access or parking needs. Starting from OpenStreetMap data, their model is enriched with detailed information specific to the studied city. After a complex simplification process, a lane-level is obtained in which nodes represent intersections, sometimes aggregated when spatially close, and edges correspond to one or several lanes, including parallel streets. Lanes are at the core of the reallocation process, and the authors distinguish several types according to their function, such as car lanes, bicycle lanes, parking access, public transport lanes, highways, or mixed lanes shared by bicycles and pedestrians. The transformation of the network must preserve strong connectivity for both bicycle and car subnetworks. Their method for redesigning the network is organized into four main steps. First, the maximum possible number of lanes dedicated to bicycles based on lanes' width is considered.

Next, they remove parking spaces and adjacent parking lanes based on the spatial distribution of residents are removed. The car lanes are then removed according to their decreasing edge betweenness centrality values. Finally, to satisfy width constraints, some lanes are further removed or rearranged.

Focusing also on bike mobility, Wiedemann and his colleagues [22] consider the reallocation problem as a trade-off between bike and car networks. Starting from a street network, an attempt to limit the impact of reallocating lanes for bicycle use is carried out. Several flow and capacity variables are considered by the optimization problem named "bike network allocation problem" (BNAP). A solution to the BNAP problem, obtained from an Integer Linear Programming (ILP) formulation, is a transformation of the original graph into two graphs, one dedicated to cars, with a strong connectivity constraint, and the other to bicycles. The quality of the resulting graphs is measured by means of travel times between a selection of locations in the city (use of Origin-Destination (OD) matrices), taking into account many parameters, including a psychological component. Their method, applied to the city of Zürich with the aim of allocating as many bike lanes as possible, resulting in a car network with many one-way streets.

Similar graph models were considered in [23], however, the motivation, problem formulation, and solution differ. The motivation stemmed from the need to free space not for bicycles, but for greening purposes. The problem was formulated as a bi-objective optimization problem, aiming to maximize the number of lanes reallocated to green spaces while minimizing the increase in distances between any two locations in the city. As in the previous work, the solution was presented as a Pareto front, and a similar observation is made: many streets originally open to traffic in both directions become one-way streets. When applied to real urban networks from 18 French cities, the method showed that up to 50% of two-way streets (one lane in each direction) were transformed into one-way streets, resulting in less than a 10% increase in the total sum of distances between any two locations in the city.

This work was further extended in [24] by introducing edge betweenness centrality on arcs to guide the selection of the lanes to be removed. The new method, tested on ten real-world street networks (common with the previous dataset), showed an improvement of the Pareto front for all cities. Also up to 50% of the two-way streets can be transformed into one-way streets with an average increase of only 5% in the total sum of distances between any two locations in the city.

2.5 Summary of the Related Works

In conclusion, while no intra-national or supernational plan or decision has been taken to mitigate the effects of climate change for urban areas, In such cities, in order to meet these challenges, several metrics have been suggested for measuring such risks entailed by such effects. For mitigation, some cities decided to set strategies for reallocating part of their street network to add vegetation to some districts and to reduce vehicle traffic. Although each city has its own characteristics, some graph-based studies have enabled better understanding of the functionalities of the network and of the effects and their modifications. Nevertheless, there remains numerous aspects which

no existing approaches manage to overcome. Indeed, the choice of the lanes to be reallocated lies at the core of many methods, this work is yet another attempt to propose an approach to mitigate such problems where EBC is utilized. EBC is used to guide which lanes in a city network can be reallocation. This work also attempts to redistribute congested areas for better efficiency of traffic flows. The next Section describes the constraints, the model, the problem formulation and especially the algorithms proposed.

3 Graph Model and Problem Formulation

3.1 Graph Model

One of the first contributions to graph theory, Euler's solution to the Seven Bridges of Königsberg problem, provided a model of a portion of Königsberg's urban street network. This corresponds to the primal graph model, which is the framework adopted in this work. In this study, a directed weighted graph is employed to represent a street network, where each arc corresponds to a lane, and specific points such as junctions, intersections, and roundabouts are represented as nodes. Figure 1 depicts an example of Le Havre, France. Each arc is weighted by a value that represents the length of its corresponding lane in the street network.



Fig. 1 Representation of Le Havre's Street Network as a Directed weighted Graph

In real-world street networks, a single street may have multiple lanes in both directions. As an objective of this work is to reduce the number of lanes, every group

of k lanes is consolidated into a single representative lane going in the same direction. Thus, a street with 2x2 lanes is represented by two arcs oriented in opposite directions in our initial. Such a pair of arcs is usually referred to as *symmetric arcs* or *opposite arcs*. If an edge in symmetric arcs is removed from the graph, this results in a single arc in one direction and the property of symmetric arcs is no longer valid.

3.2 Objectives, Restrictions and Constraints

The main objective of this work is to reduce the number of lanes in the street network to free up space. However, in practice, some constrains must remain true and hence this defines the types of operation allowed. One major restriction is that adding lane(s) to the original city network is omitted as it is beyond the scope of this work. Also, every part (i.e. place) in the city network must still be accessible. This implies that removing all arcs linking two nodes are not permitted. Furthermore, all junctions and intersections must not be collapsed, this implies that the set of nodes must remain unchanged throughout the process. Consequently, any one-lane street has to remain unchanged 263 between the original and modified graphs to preserve accessibility constrain.

Formally, starting from a weighted directed graph $G = (V, A)$, the modified graph $G' = (V', A')$ must verify: $V' = V$. Furthermore, if arcs (u, v) and (v, u) are symmetric arcs, then at least one of them has to be present in A'. In other words, if u and v are neighbors in G then they are still neighbors in G'.

In addition to these restrictions, both the original graph and the modified graph resulting from the lane removal operations must be strongly connected (i.e. a directed path must exist between any two nodes 269 in the graph) Hence forth, this property is referred to as 'strong connectivity'.

3.3 Problems Formulation

In graph-theoretical terms, the main goal is to reduce the number of symmetric arcs in the graph while preserving both strong connectivity and accessibility. Starting from this general statement, multiple problem formulations may be derived.

If the goal is to remove the maximum number of symmetric arcs, then this becomes an optimization problem. Without taking the accessibility constraint into account. This corresponds to the problem of finding the *Minimum Strongly Connected Spanning Subgraph* (SCSS) known to be NP-Hard [25]. However, this work is also close to already existing problems like the *Network Sparsification* with performance trade-offs, where the goal consists of keeping a smaller set of edges while preserving certain properties. Strong connectivity is often imposed as a hard constraint, while the objective is to minimize distance distortion [26].

In the context of this study, two variants are proposed, both are bi-objective, sharing the same objective in reducing the number of symmetric arcs. However, the first has another specific objective of minimizing the distance-based measure. This distance-based measure is the shortest sum of distances between every pair of nodes in the network. This is commonly known as All-Pair-Shortest-Part (APSP). The another

specific objective of the second variant is to divert and distribute traffic away from city center or congested areas in the original network using some graph information.

Many works have already been devoted to problems similar to the first variant, but most of them rely on the construction of a spanner [27], thereby ignoring the constraint of neighborhood conservation.

In this variant, the All-Pairs Shortest Paths (APSP) measure is considered. If we denote $d(a, b)$ the value of the shortest path from node a to node b, the APSP value results in the sum of the distances of all pairs of nodes (note that $d(a, b)$ may be different than $d(b, a)$):

$$APSP(G = (V, A)) = \sum_{(a,b) \in V \times V} d(a, b)$$

This formulation results in a bi-objective optimization problem, where the first criterion is the number of symmetric arcs, and the second is the APSP measure.

For the second variant, the main objective is to divert the traffic away from the congested part of the city by removing some symmetric arcs. Unlike distance-based metrics that can be obtained directly from the graph, actual traffic data are usually not available. To circumvent this issue, an alternative graph-based metric is adopted, the Edge-Betweenness Centrality (EBC). Indeed, according to the results of the studies presented in Section 2.3, streets with high EBC values ought to reflect a street with more traffic flow than a lower one. Furthermore, it has been shown that, in many cities, urban centers are generally hotter (i.e. higher heat islands) than their outskirts [28, 29]. In this context, it is intuitive that removing arcs with high EBC values ought to divert and distribute the traffic away from city centers (or congested areas) and hence freeing space for vegetation. Therefore, a solution ought to have a dual positive effects on both reducing number of symmetry arcs and limiting temperature increases.

The next Section proposes generic methods utilizing the Edge Betweenness Centrality measures for both variants.

4 Edge-Betweenness Centrality-based Methods

An algorithm for removing arcs while maintaining the strong connectivity of the graph was originally proposed in [23] and further improved in [24] by introducing the edge-betweenness centrality (EBC) value of the arcs (presented in Section 2.4). The algorithm was designed to address the first variant of the problem, reducing the number of symmetric arcs while minimizing the APSP measure.

The method involves identifying a cycle oriented in the direction opposite to that of the symmetric arc chosen for removal. Let (u_i, u_j) be a symmetric arc chosen for removal. If there exists a cycle $(u_0, u_1, u_2, \ldots, u_k, u_0)$ containing the symmetric arc (u_j, u_i), then (u_i, u_j) can be safely removed without affecting the strong connectivity of the graph.

4.1 Generic Algorithm

A new algorithm is developed, based on the previous one, and is used a basis for both variants. The algorithm comprises an iterative process with four steps: (i) computation of edge-betweenness centrality for all arcs, (ii) selection of a symmetric arcs for removal, (iii) a DFS based cycle detection , and (iv) arc removal. The process is iterated by returning to step (i) or (ii) depending on the success of step (iii). The process terminates when no symmetric arcs can be removed without violating the constraints or a specific stopping condition is reached, for example, more than specified 20% of symmetric arcs have been removed. The Generic Algorithm is described depicted in Algorithm 1.

Algorithm 1 Generic Algorithm

Require: Street Network G
1: $list_of_candidates \leftarrow$ all symmetric arcs of G
2: Compute EBC for all arcs in G
3: Sort($list_of_candidates$) according to EBC values
4: Evaluate($stopCondition$)
5: **while** $list_of_candidates \neq \emptyset$ **and** $\neg stopCondition$ **do**
6: $a \leftarrow$ first arc of $list_of_candidates$
7: Remove a from $list_of_candidates$ ▷ $\bar{a}$ is the symmetric arc of a
8: $c \leftarrow$ find a cycle that includes $\bar{a}$
9: **if** c exists **then**
10: Remove a from G
11: Remove $\bar{a}$ from $list_of_candidates$
12: Compute EBC for all arcs in G
13: Sort($list_of_candidates$) according to EBC values
14: Evaluate($stopCondition$)
15: **end if**
16: **end while**

4.2 Variants

For a given arc, the EBC value is the number of shortest paths passing through this arc for all pairs of graph vertices.

For the first variant, the APSP is the second objective. Suppose a is a symmetric arc whose EBC value is 0, then removing a from the graph does not change the APSP value. Following this idea, intuitively, removing a symmetric arc that participates in few shortest paths is likely to have less impact on the APSP value than removing a symmetric arc with a high EBC value. Therefore, for the first variant, candidate arcs in listed in ascending order of EBC value, so that the first element of list of candidates is the symmetric arc with the lowest EBC value. For brevity, the symmetric arc with the lowest EBC value at any instance is referred to as $L - EBC$. It has been shown

that the results obtained from selecting E-LBC approach is superior to those reported in [24].

For the second variant, the main objective is to divert traffic away from the city center. Based on previous work presented in Section 2.3, we hypothesize that streets with denser traffic correspond to arcs with the highest EBC values. Accordingly, for this variant, we sort the list of candidate arcs in decreasing order of EBC value, so that the first element of list_of_candidates is the symmetric arc with the highest EBC value. We call the corresponding algorithm H-EBC, and we show that the transformed network exhibits high EBC value arcs in areas outside the city centers.

For the second variant, the main objective is to divert traffic away from the city center or congested area. Based on previous work presented in Section 2.3. following similar idea, and intuitively, streets with denser traffic ought to correspond to arcs with high values of EBC. Therefore, in the opposite manner, candidate arcs in listed in descending order of EBC value, so that the first element of list of candidates is the symmetric arc with the highest EBC value. For brevity, the symmetric arc with the lowest EBC value at any instance is referred to as $H - EBC$. The results of this approach have shown that the transformed networks higher EBC arcs are shifted away from city centers or congested area with better distribution of high EBC arcs.

5 Experiments and Analyses

5.1 General Workflow and Dataset Description

The real street network datasets, representing fourty eight cities from OpenStreetMap [30] are used in this work to study, assess and verify the proposed algorithms. The original city networks are extracted and converted into the DGS format used by the GraphStream library [31]. Prior to applying the algorithm, preprocessing is necessary to ensure that the network conforms to predefined as stated in the previous section. It mainly comprises the following :

1. All dead-end streets (a.k.a cul-de-sac) are removed;
2. The network must be strongly connected; this is verified by the Kosaraju's algorithm [32]. If it is not, every unreachable node is removed until strong connectivity is achieved;
3. When two (or more) lanes in a street run in the same direction, they merge to form a single edge.

In all networks (forty-eight cities) used in this study, this initial step removes only a negligible fraction of nodes. Table 1 elaborates these forty-eight different cities. Their networks Forty-eight different cities from many varies from 480 arcs to 12,517 arcs. The ratio of the symmetric arcs to the total number of arcs ranges from 34% for Manhattan to 94% for Hamm.

5.2 Results for the First Variant

In the first variant, the bi-objective aims at minimizing both the APSP value and the number of symmetric arcs. These objectives are inherently conflicting. Indeed, as the

City	Node	Arcs	APSP	Sym. Arc	City	Node	Arcs	APSP	Sym. Arc
Noosa Heads	241	480	129	144	Honfleur	358	752	386	257
Dubrovnik	457	1006	1832	396	Fougères	758	1604	1036	537
Vichy	772	1720	917	538	Périgueux	827	1902	1417	678
Troyes	1244	2766	3793	948	Bergerac	1225	2826	4388	1079
Auxerre	1276	2890	4714	1050	Geneva	1509	3314	5085	976
Angoulême	1583	3331	6761	1041	Móstoles	1682	3401	12107	894
Brussels	2051	3989	21383	866	Oxford	1799	4277	16295	1896
Baguio	1835	4306	16473	1930	Getafe	2585	4864	42035	1076
Leganés	2488	4959	24113	1183	Gliwice	2198	5136	28108	1979
Amiens	2490	5208	23034	1583	Poitiers	2470	5411	26552	1855
Rzeszów	2525	5826	35760	2272	Launceston	2509	5845	45772	2358
Nice	2981	6127	53504	1729	Radom	2669	6186	34878	2228
Hagen	2573	6365	43447	2723	Boulder	2460	6386	29040	2636
Saarbrücken	2978	6770	63865	2568	Avignon	3263	6895	45364	2241
Burgos	3555	6992	58686	1638	Albacete	3338	6993	93094	1898
Reims	3192	7151	43290	2366	Pattaya	3013	7192	53650	3161
Lyon	3739	7413	65528	1436	Le Havre	3095	7810	37788	3061
Bordeaux	3982	8088	71068	1924	Hamm	3054	8103	69764	3821
Białystok	3815	8618	83050	3021	Limoges	3871	8766	80138	3092
Valladolid	4520	8860	106311	1872	Zurich	3822	8941	69816	3266
Brunswick	3799	9072	105955	3619	Manhattan	4423	9534	142678	1633
Ljubljana	4149	9757	139548	3930	Padua	5110	10609	146699	3535
Prato	5783	11592	312358	3368	Krabi	4966	11680	1015297	5132
Mannheim	5261	12298	193072	4241	Catania	6170	12517	250172	3287

Table 1 Real city datasets

more symmetric arcs are removed, the more the total travel distance (represented by the APSP) increases.

The same bi-objective problem was addressed in [24]. The work introduces the Self-Adaptive Edge Betweenness Centrality (S-IEBC) algorithm, a stochastic algorithm that seeks to balance computational efficiency with solution quality. The main idea of the S-IEBC algorithm is to iteratively remove symmetric arcs based on their EBC values under the threshold of the self-adaptive mechanism.

At the time of its publication, S-IEBC provided the best results for the problem. The algorithm propose in this paper is actually an adaptation of the generic algorithm presented in the previous section. It is referred to as the *L-EBC* algorithm for brevity and is presented in 2.

The results produced by L-EBC not only are generally superior, but also simpler than that of the S-IEBC, although this improvement comes at the cost of higher computational time. As the problem is bi-objective a Pareto front is a common method to display the result. However, as this main objectives of this works is to determine possible number of symmetric arcs that can be removed from the street network with respect to its APSP. Therefore, two most critical values are selected for illustration of the result for each city. These are the APSP, minimum percentage of remaining symmetric arcs which illustrated in Figure 2.

Note that, in theory, more than 95% of the symmetric arcs can be removed, except for two cities: Nooseheads and Dubrovnik. A close observation reveals the fact that

Algorithm 2 Lowest First Edge Betweenness Centrality (L-EBC) Algorithm

Require: Street Network G

$list_of_candidates \leftarrow$ all symmetric arcs of G
Compute EBC for all arcs in G
Sort($list_of_candidates$) in increasing order of EBC values
while $list_of_candidates \neq \emptyset$ **do**
    $a \leftarrow$ first arc of $list_of_candidates$
    Remove a from $list_of_candidates$
    $c \leftarrow$ find a cycle that includes $\bar{a}$ ▷ $\bar{a}$ is the symmetric arc of a
    if c exists **then**
        Remove a from G
        Remove $\bar{a}$ from $list_of_candidates$
        Compute EBC for all arcs in G
        Sort($list_of_candidates$) in increasing order of EBC values
    end if
end while

this is due to the fact that both cities have many symmetric arcs that are also bridges and, hence preventing their removal. Figure 3 depicts the such situations resulting from the algorithm.

Careful examination of extreme solutions shown obtained by the two algorithms (as shown in Figure 4) fall into four categories :

- L-EBC solutions that dominate S-IEBC solutions.
- S-IEBC solutions that dominate L-EBC solutions.
- Solutions where L-EBC yield better APSP than those of S-IEBC.
- Solutions where S-IEBC yield better minimum percentage of remaining symmetric arcs.

In practice, however, the solutions fall into only two categories. For 34 instances, the L-EBC solutions dominate S-IEBC solutions, while for the 14 remaining instances, S-IEBC performs better than L-EBC with respect to the APSP objective. Thus, L-EBC outperforms S-IEBC in minimizing the number of symmetric arcs for all instances. For the 14 instances in which the APSP value is better for S-IEBC solutions, it is worth noting that the number of remaining symmetric arc is not identical as illustrated in Figure 5 (left).

In Figure 5 (right), the same number of remaining symmetric arcs is selected from both algorithms in order to evaluate the effectiveness of the APSP objective. The selected value corresponds to the extreme solution produced by either algorithm and is defined as:

$$S_{\min} = \min\left(\max(S_{\text{S-IEBC}}), \max(S_{\text{L-EBC}})\right),$$

where S denotes the percentage of remaining symmetric arcs in the network.

The results show that, for most instances, L-EBC outperforms S-IEBC, except for three cities: Bergerac (France), Gliwice (Poland), and Albacete (Spain). if their results are shown by means of pareto font. However, an interesting observation appears in city of Gliwice, if their results are displayed using pareto front as shown in Figure

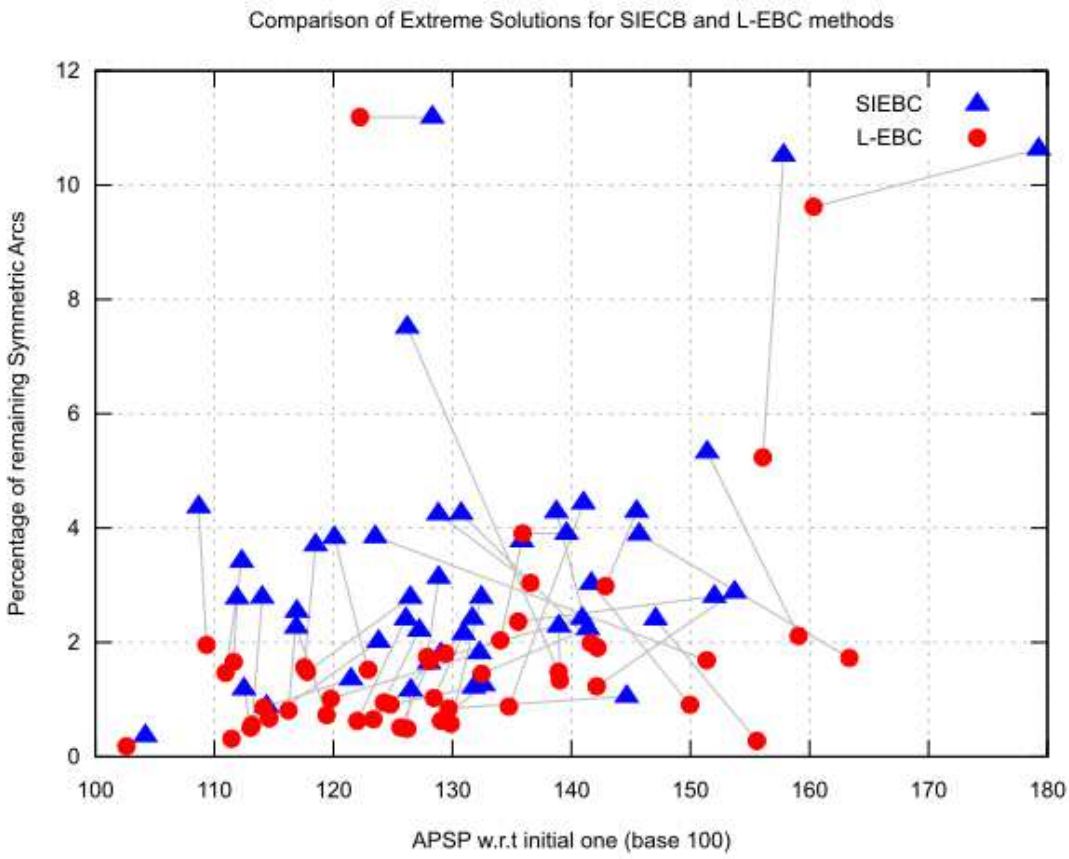


Fig. 2 Comparison of the extreme solutions produced by L-EBC and S-IEBC on the 48 instances. For most instances, more than 95% of symmetric arcs can be removed without loosing the strong connectivity of the street network. Each grey line links the solutions produced by both algorithms for the same city instance.

6, neither algorithm is proven superior in all instances of APSP with respect to the number of symmetric arcs removed. The same observation holds true for almost all cities experimented in this study. Topology of each city may play the central role for such result.

Another common metric of this kind of study like this the HyperVolume. It is a classical metric/indicator used to evaluate the effectiveness of bi-objective optimization methods by comparing their Pareto fronts. This metric measures the volume of the objective space dominated by the obtained solutions with respect to a reference point representing the worst solution among all solutions, with an appropriate margin. The size of the dominated area between the solutions and the reference point

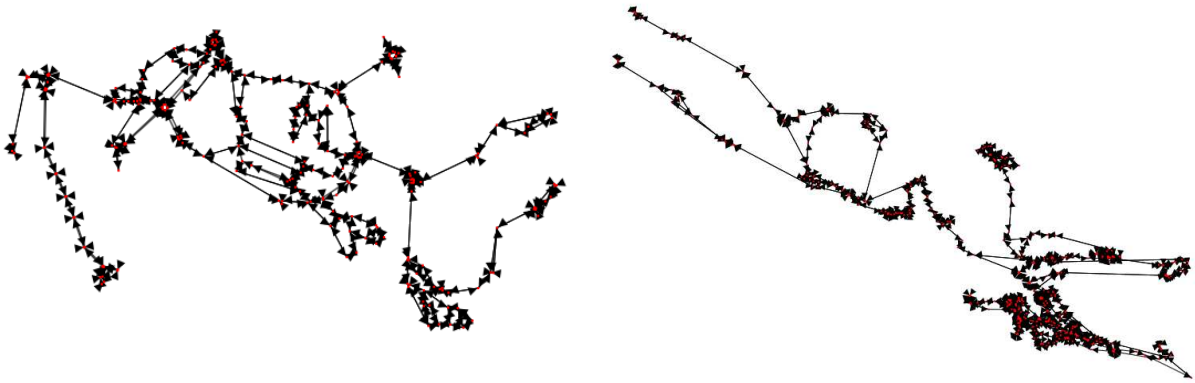


Fig. 3 The street networks of Nooseheads and Dubrovnik have many symmetric arcs that are bridges.

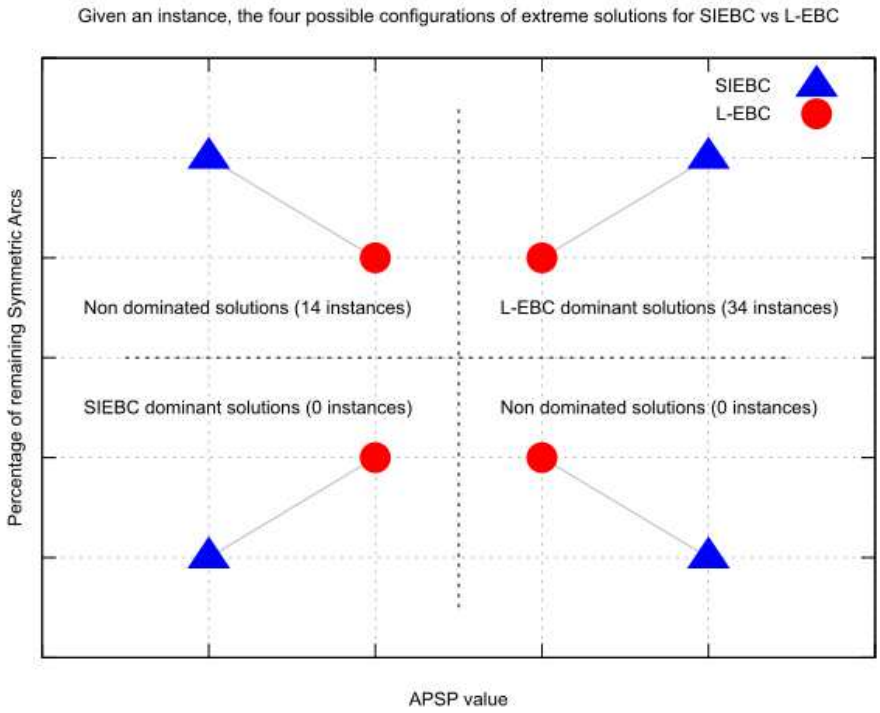


Fig. 4 The four possible position of S-IEBC solution relative to the L-EBC solution for a given instance.

reflects the effectiveness of the model, as illustrate in Figure 7 illustrates the Hyper-Volume values obtained by both algorithms. The results clearly indicate that L-EBC demonstrates superior overall performance across all tested street networks.

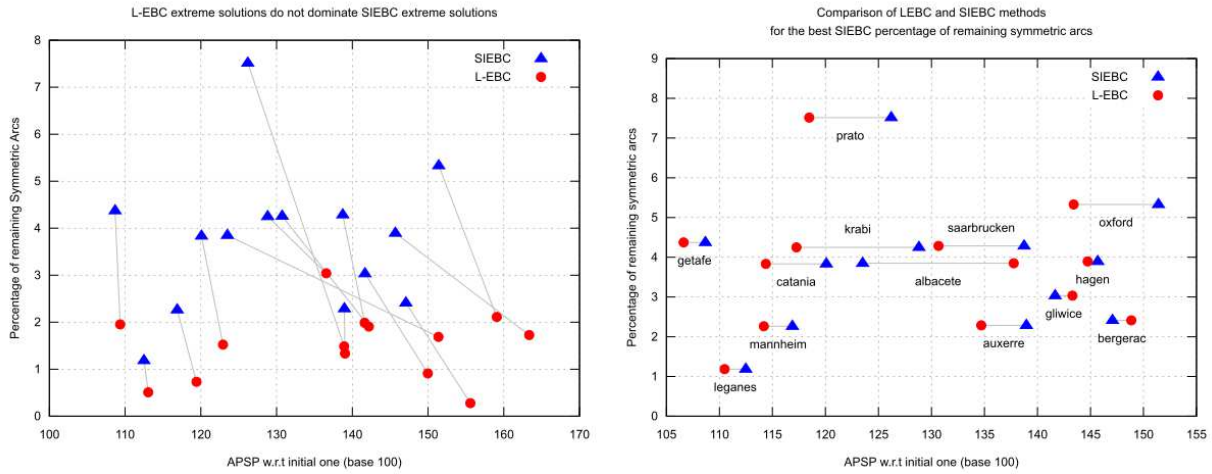


Fig. 5 On the left, illustration of the non dominated solutions of both algorithms. On the right, comparison of the results obtained by both algorithms for the best percentage of remaining symmetric arcs obtained by S-IEBC method. The city of Brunswick is omitted for clarity.

5.3 Results for the Second Variant

Indeed, the main purposes of this second variant is to show that the algorithm that be able to modify the spatial distribution of the arcs with the highest EBC values, a property that might be used for mitigating the Urban Heat Island problem. Note, also that the previous contribution of S-IEBC is no of the real concern in this variant, and hence no comparison between results from S-IEBC is included.

In this Section, the distribution of EBC values is analyzed and the results are shown to be in accordance with truncated power-laws. This is followed by the detail description of the algorithm proposed to modifying the street network where highest EBC removal is considered first. Finally, two new metrics for evaluation of the spatial distribution are proposed.

5.3.1 EBC distribution

At first glance, when observing the plot on a linear scale, the distribution of EBC values may appear compatible with a power law. However, when represented on a log-log scale, it does not exhibit the approximately linear behavior expected of a power-law distribution (left part of Figure 8). Instead, the distribution shows an approximately linear decline for small values, followed by a sudden steep drop in the tail as illustrated on Figure 8 (right part). This behavior is typical of a truncated (or cutoff) power-law distribution, in which power-law scaling dominates at small and intermediate values, while the largest values are suppressed, leading to a faster decay in the tail.

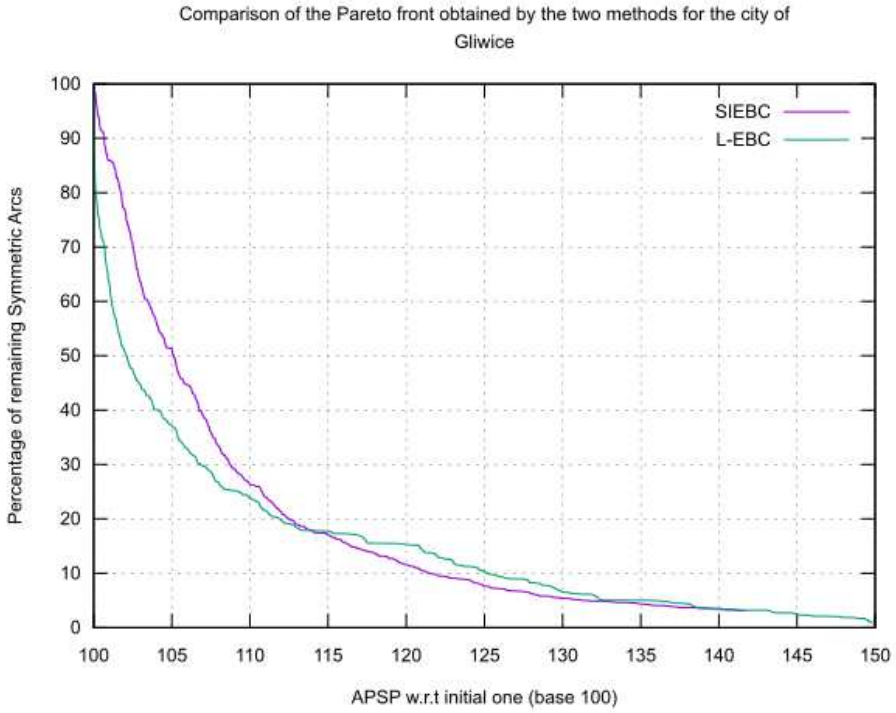


Fig. 6 Comparison of Pareto fronts for three instances of L-EBC and S-IEBC methods for Gliwice city

The analysis of the distribution indicates that only a few arcs exhibit the largest values of EBC. Consequently, unlike the first variant, where the objective is not to remove as many symmetric arcs as possible. Instead, the main objective is to removing the top k% of arcs with the highest EBC values (where k is the number specified by the users. Higher value of k implies more arc removals). This work proposes the $H - EBC$ algorithm for this process. For brivity, k% of arcs with the highest values of EBC is referred to as top-k% arcs.

5.3.2 The Hightest First Edge Betweenness Centrality (H-EBC) Algorithm

The Highest First Edge-Betweenness Centrality (H-EBC) algorithm, proposed for the second variant, is also adapted from the generic algorithm as described in Section 4. It is depicted in Algorithm 3.

Applying the algorithm results in a shift of the region containing the top k% arcs, as illustrated on the city of Troyes in Figure 9. Figure 9 illustrates the result from the application of the H-EBC to shift of the region containing the top k% arcs to the city of Troyes. Additional results are provided in the Supplementary Materials (results for the 48 cities).

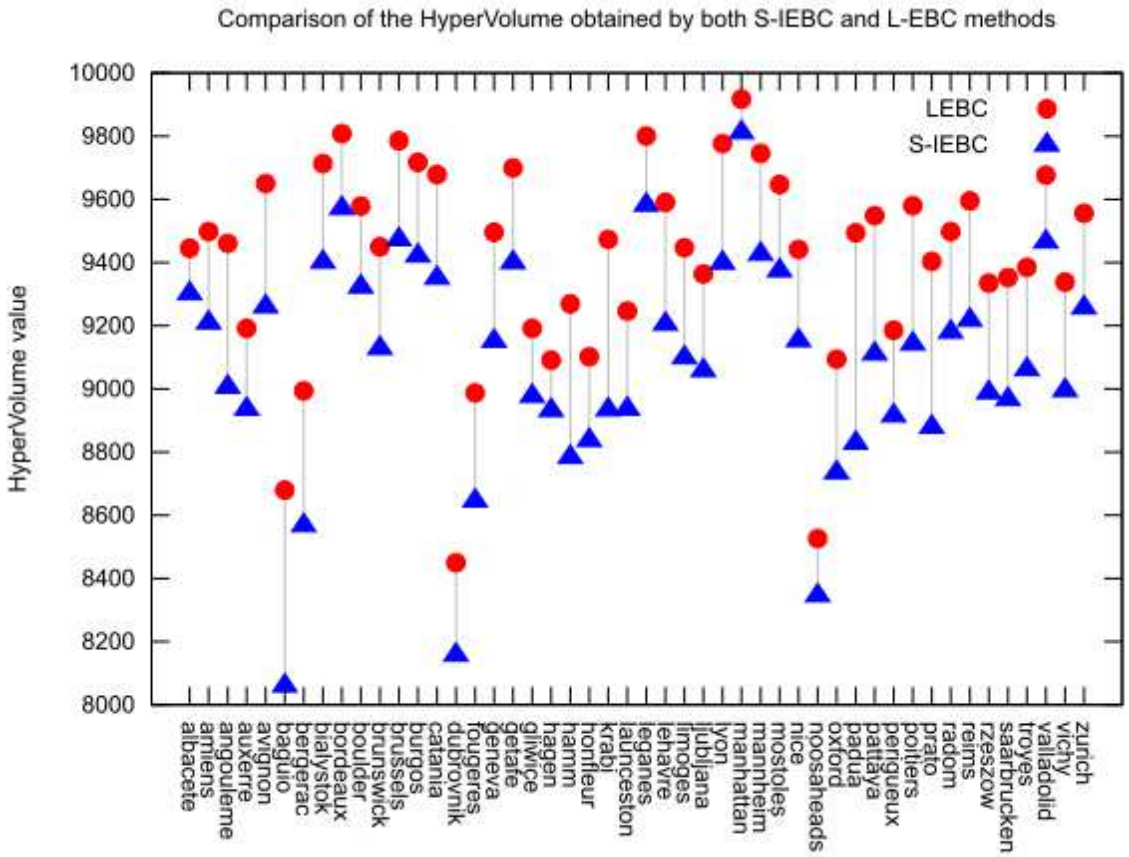


Fig. 7 Comparison of the HyperVolume value for Bi-Objective(Remaining Symmetric Arcs, APSP) for all 48 cities.

5.3.3 Evaluation

The perfomance of H-EBC algorithm, like any others, requires evaluation. In this work, two metrics are proposed to evaluate the modification of the distribution of top-k% arcs we propose two metrics. They are meant to be used complementary of each other. The A^k_{orig} is noted as the top-k% arcs in the original street network and A^k_{hebc} the top-k% arcs in the street network after the application of the H-EBC algorithm.

For both metrics the distance considered is the Euclidean distance and not the classical graph-based distance related to the shortest paths. Indeed, the Urban Heat

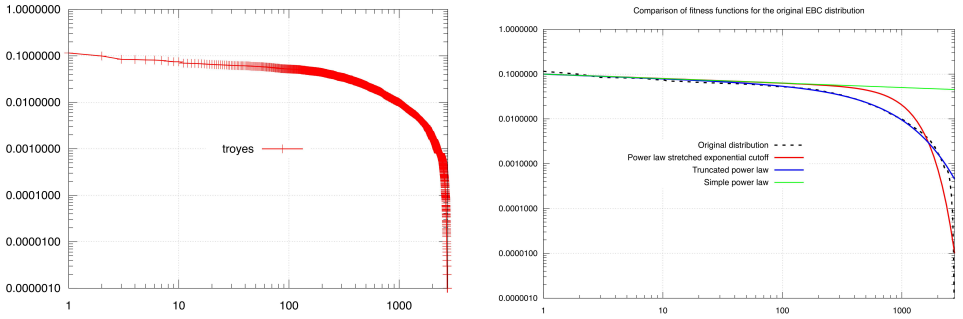


Fig. 8 EBC distribution (logarithmic scale on the left) and several fitness functions: power, truncated power-law and stretched exponential cutoff. Example for the French city of Troyes.

Algorithm 3 H-EBC Algorithm

Require: Street Network $G = (V, A)$, k the percentage of symmetric arcs to remove

$list_of_candidates \leftarrow$ all symmetric arcs of G
Compute EBC for all arcs in G
Sort($list_of_candidates$) in decreasing order of EBC values
$nbOfArcsToRemove \leftarrow k|A|/100$
$nbOfRemovedSymArcs \leftarrow 0$
while $nbOfRemovedSymArcs \leq nbOfArcsToRemove$ **do**
    $a \leftarrow$ first arc of $list_of_candidates$
    Remove a from $list_of_candidates$ ▷ $\bar{a}$ is the symmetric arc of a
    $c \leftarrow$ find a cycle that includes $\bar{a}$
    if c exists **then**
        Remove a from G
        $nbOfRemovedSymArcs \leftarrow nbOfRemovedSymArcs + 1$
        Remove $\bar{a}$ from $list_of_candidates$
        Compute EBC for all arcs in G
        Sort($list_of_candidates$) in decreasing order of EBC values
    end if
end while

Island (UHI) effect which is the general environmental issue that related to the hot temperature in the city area is typically analyzed as a spatial gradient in continuous Euclidean space, often as a function of distance from the city center.

The first metric measures the distance between the centroid of the two sets relative to the geometric median of the city. The geometric median of the city, C is the node that minimizes the average Euclidean distance. If V denotes the set of points in the network then:

$$C = arg\min_{w} \sum_{w_i \in V} distance(w, w_i)$$

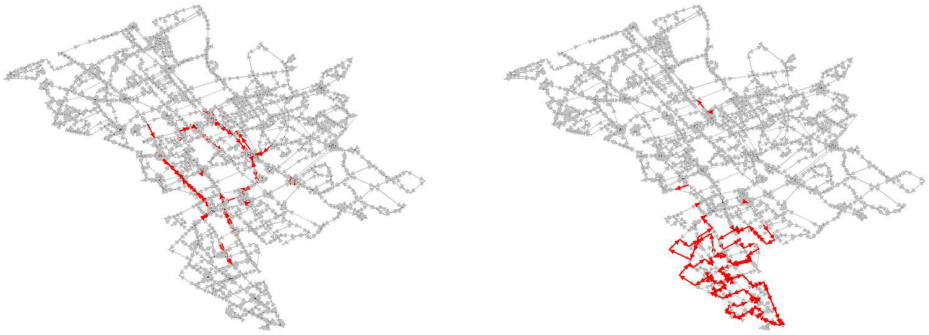


Fig. 9 Spatial distribution of the top-5% arcs for the French city of Troyes. Before removing any arcs (left side), and after removing the top-5% arcs (right side).

In fact, the centroid can be used instead of the geometric median, however, the geometric median is chosen for its more robustness to outliers than the centroid.

The position of the centroid C_A, of the set A of arcs, is computed as the average value of the coordinates of the extremities of all the arcs of A:

$$(x_{C_A}, y_{C_A}) = \left(\sum_{e \in A} x_e/|A|, \sum_{e \in A} y_e/|A| \right)$$

where $e = (v_0, v_1)$ and $(x_e, y_e) = ((x_{v_0} + x_{v_1})/2, (y_{v_0} + y_{v_1})/2)$
Assuming that $k = 5$, Figure 10 represents the geometric median, the top 5% arcs their centroid.

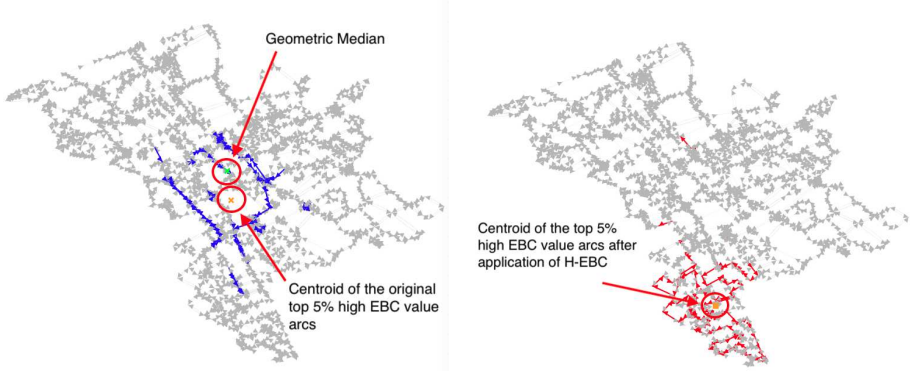


Fig. 10 Localization of the Geometric Median, and of the centroids of the top-5% arcs, in the original street network (left) and after the application of the H-EBC algorithm (right).

In considering the difference between these two distances. Nothing, as the size of cities may vary a lot, and in order to have a comparison basis between two cities, the difference is standardized by dividing it by the distance between the geometric median and the most peripheral node, P, obtained as:

$$P = arg\max_{w} \sum_{w_i \in V} distance(w, w_i)$$

The first metric is can be defined as:

$$M_{center} = \frac{distance(C_{A^k_{hebc}}, C) - distance(C_{A^k_{orig}}, C)}{distance(P, C)}$$

In interpretation, the value of M_{center} can range between -1 and 1. If C is assumed to be close to the city center, then a positive value of M_{center} indicates that the main streets have shifted away from the city center.

The second metric M_{spread}, measures the spatial spread of the arcs. For that, for each set, A, we compute the mean absolute deviation from the centroid:

$$D(A) = \frac{1}{|A|} \sum_{e \in A} distance(e, C_A)$$

which leads to the second metric:

$$M_{spread} = \log_2 \left(\frac{D_{A^k_{hebc}}}{D_{A^k_{orig}}} \right)$$

In interpretation, a value close to 0 indicates that the two sets of arcs have similar spatial spreading. A positive value of M_{spread} suggests that the main streets are more spatially dispersed after the application of the H-EBC algorithm, while a negative value indicates the opposite.

The synthesis of the results for the 48 cities are presented in Figure 11 and Figure 12. Figure 11 reveals the M_{center} and Figure 12 reveals the M_{spread} respectively.

Considering the M_{center} metric, for most cities, the value of $M_{center} > 0$, that indicates a shift of these top-5% arcs from the city center to other regions of the city. For these cities, the objective of moving the centroid of the top-5% arcs is achieved. However, there are two notable exceptions: Mostoles and Getafe. For both cities, it is observed that the position of the centroid is closer to the city center after the application of the algorithm. This can be explained by the structure of the cities. They consist of several clusters, defined as groups of nodes that are strongly connected within themselves but only weakly connected to each other. When arcs belonging to the top-5% are distributed across several clusters, then the removal of a single arc linking two clusters entails a modification of the values of many arcs belonging to the

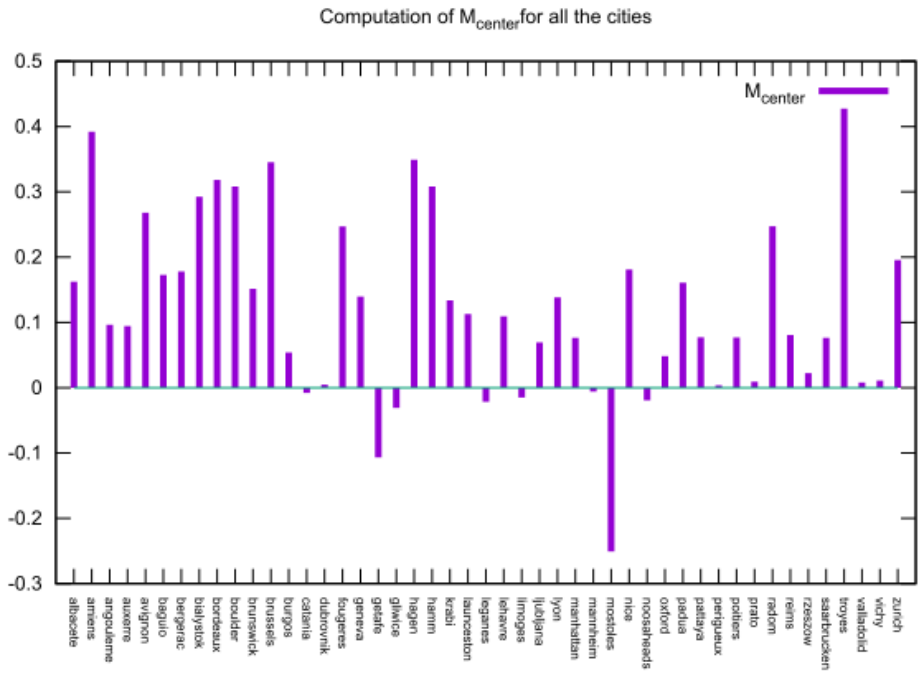


Fig. 11 M_{center} measures the modification of the centrality of the distribution of the top-5% arcs. Line 0 means that centrality did not change.

cluster most distant from the city center. The consequence is a concentration of the top-5% arcs around the city center. This is illustrated on Figure 13 for Mostoles city.

For the M_{spread} metric, a similar phenomenon occurs. For most cities, the value of $M_{spread} > 0$, that indicates a better dispersion of the top-5% arcs in the city. There are, however, three notable exceptions: Mostoles, Noosaheads and Boulder. For these cities the observation depicts that the spreading was better before the application of the algorithm. The cluster-based structure of both Mostoles and Noosaheads explain this phenomenon, as it was the case for the M_{center} metric. Boulder, however, does not exhibit such an organization. But the top-5% arcs seem to be organized as long chains forming a tree-structure (as shown in Figure 14). Thus, when such long chains are cut, the arcs distant from the city center loose their importance from the EBC point of view, leading to a concentration of the top-5% arcs.

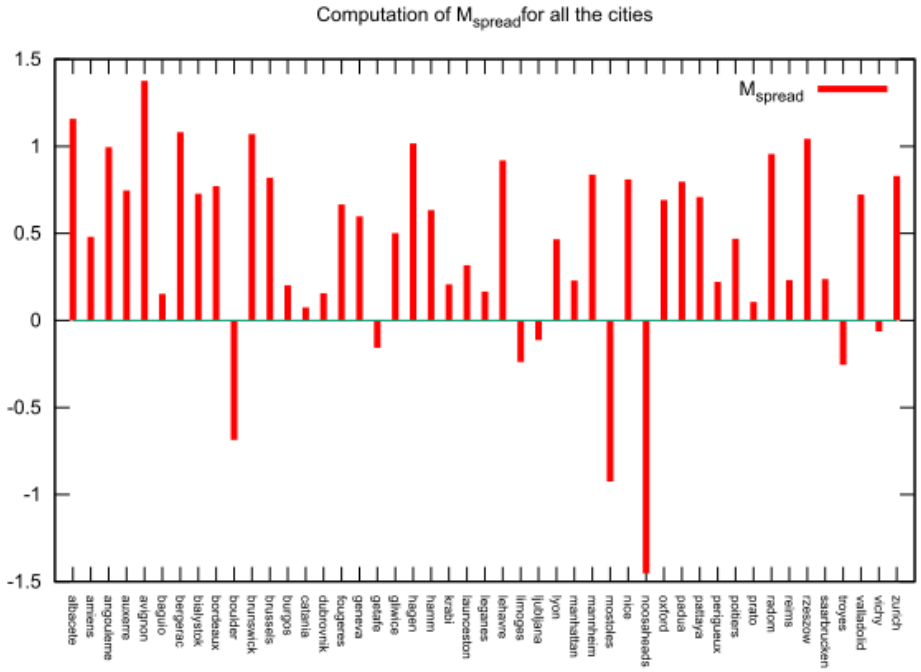


Fig. 12 M_{spread} measure the modification of the spreading of the top 5% arcs. Line 0 means that this spreading remains unchanged.

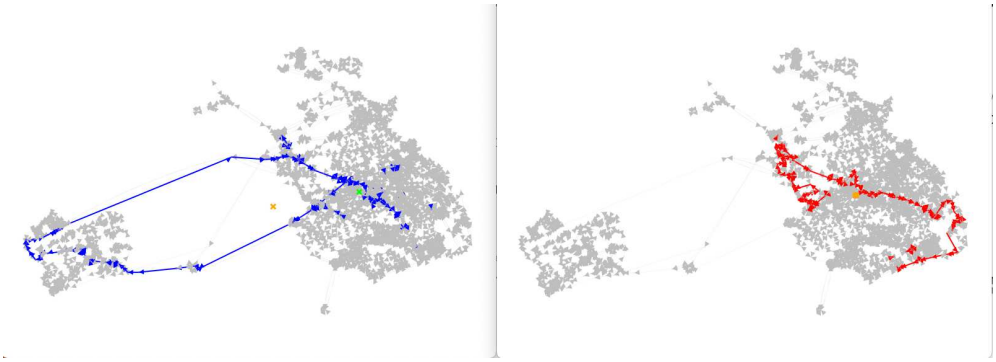


Fig. 13 Evolution of the top 5% arcs in the city of Mostoles, in the original street network and after the application of the algorithm.

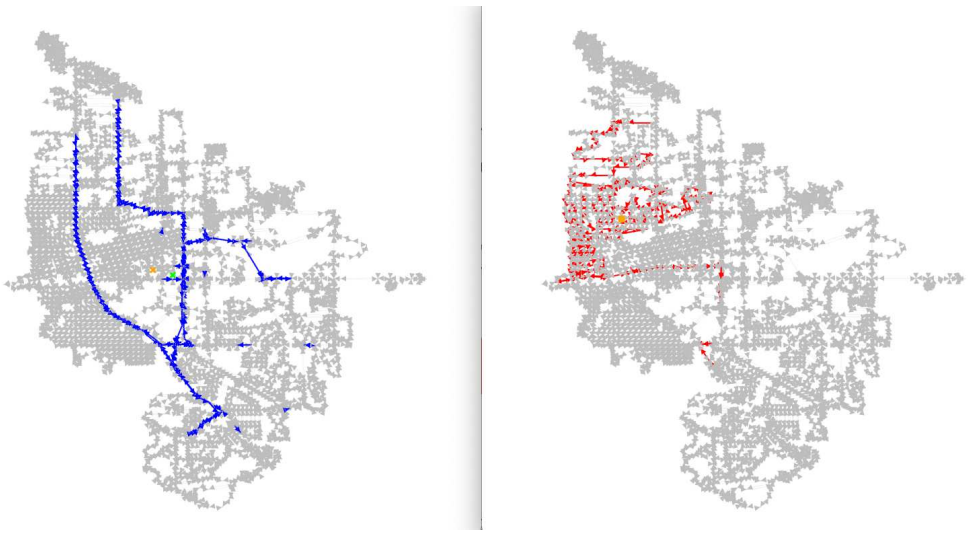


Fig. 14 Dispersion of arcs belonging to the top-5% arcs, before (left) and after (right) the applciation of H-EBC algorithm.

6 Conclusion and Perspectives

If any reminder is still needed, daily news constantly reminds us that major climate change is already underway. Due to the inertia of the climate system, human societies must already adapt to its impacts and will have to continue adapting over the coming decades.

In parallel with this ongoing evolution, an ever-increasing share of the global population is living in urban areas, where heat concentration phenomena, commonly referred to as Urban Heat Islands (UHIs), coincide with episodes of intense precipitation that can lead to severe flooding due to the widespread imperviousness of urban surfaces.

One strategy adopted by some cities consists of reclaiming portions of artificialized surfaces and converting them into green areas, thereby simultaneously reducing soil sealing and mitigating the effects of UHIs. Such reclaimed areas can be obtained through the reallocation of space currently occupied by urban street networks.

In this work, a generic algorithm based on edge betweenness centrality (EBC) is proposed to identify arcs corresponding to traffic lanes that can be reallocated for urban greening. Two variants of road-space reallocation have been proposed.

The first variant aims to maximize the number of traffic lanes that can be reallocated while preserving accessibility within the urban network. As a secondary objective, it seeks to minimize the increase in distances between all pairs of nodes in the network.

A strategy based on selecting arcs with the lowest betweenness centrality is adopted. This results in an algorithm L-EBC. The algorithm managed to produce high quality solution to address the problem.

It simultaneously achieves a high level of reclaimed space and minimizes the impact on the sum of shortest-path distances, commonly referred to as the All-Pairs Shortest Paths (APSP) metric.

The second variant pursues a different and more targeted objective. The main objective is to free space in city centers and congested area while reallocating traffic lanes associated with the highest estimated traffic levels from central areas toward more peripheral zones.

To achieve this objective, the generic algorithm is developed into the H-EBC algorithm, which selects arcs according to their highest EBC values. In the analysis of its performance, in the analysis, we have considered only the top-k% arcs, namely the k% of arcs with the highest EBC values can be removed where user can specify the value of k.

The original network and the solution network are compared with respect to the displacement of the most influential arcs in terms of estimated traffic impact. The work also introduced two new metrics. The first one, M_{center}, evaluates the displacement of the centroid of the top-k% arcs before and after the application of the algorithm with respect to the geometric median of the city. The second one, M_{spread}, evaluates the spatial dispersion of the top-k% arcs before and after the application of the algorithm.

It must be borne in mind that, there does not exist rules or heuristics applicable to all type of city structure. In reality, each city is usually considered in isolation, with its own constraints, by all concerned. This, in turn, implies that there cannot be a reallocation algorithm applicable to all cities. Also, in practice, reallocation of street surfaces is not a task of any individual, especially an expert in network topology. There may be several factors which cannot be overlooked, such as important monuments, local administrative buildings, etc. These may render reallocation of some street lanes infeasible. This work is intended to offer possible solutions or guide those such as city planners, urban designers as starting points where they can further consideration can be based. They can then be assured what basic theoretical groundwork are possible.

This work has opened several research perspectives, some of which are already the subject of an ongoing collaboration with other research groups.

Investigation is being carried out on the coupling of the approach introduced in the second variant of the algorithm with a model describing temperature variations in urban areas benefiting from an increase in vegetated surfaces.

In collaboration with another research team, an exploration of how the selection of arcs to be reallocated for greening purposes can be informed by actual temperature measurements collected in urban environments.

Also, incorporation satellite data to model temperature gradients within urban areas can be carried out. Such information could then be used to apply the H-EBC algorithm in a targeted manner, focusing on the areas experiencing the highest temperatures, with the objective of reallocating traffic lanes in these locations and increasing vegetation coverage.

Future version of the algorithm can incorporate real and concrete knowledge from city planners and urban designers. This is possible that some of such knowledge is not city dependent and is applicable to all situations. Such knowledge can be transformed into heuristic-like format and be incorporated into the algorithm.

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