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Bi-objective Optimization for Reducing Urban Network Sprawl

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Abstract—The urban population is steadily rising, with city growth and an increase in land use as its corollaries. As temperatures rise due to climate change, there is an urgent need for green cities. Addressing this requires the reallocation of portions of already artificialized soils for the purpose of greening a city. The possibility of repurposing some urban spaces, specifically by reducing street network sprawl, received much attention recently. In this work, the urban street network is modelled as a strongly connected directed graph. The problem can be formulated as a bi-objective optimization problem. Based on a particular property, several algorithms are proposed to reduce the number of arcs in the network while preserving the strong connectivity property. The solutions generated by these algorithms collectively build a Pareto front for a particular city. Using OpenStreetMap data, the proposed algorithms are applied to several French cities. The results demonstrate that a substantial number of symmetric arcs, from 15% to 50% in some cities, can be removed from the street network with a limited increase on the distances between locations in the city, between 5% to 15%. This work constitutes an additional contribution to the methods designed to mitigate the effects of climate change on urban areas.

Index Terms—Bi-objective Optimization, Green Cities, OpenStreetMap, Pareto Front, Street Network Sprawl, Strongly Connected Directed Graph

I. INTRODUCTION

The latest IPCC report paints a picture of an unpleasant future due to rising temperatures and their consequences. It has been shown that the rise in temperature results from an increase in the concentration of greenhouse gases (GHGs) in the atmosphere. According to IPCC statistics, transport systems are responsible for 15% of these emissions just after agriculture and industry, and this share is mainly due to gasoline engines [1]. In order to reduce this impact, at the end of 2022, EU decided to ban new fossil fuel cars by 2035 in Europe. But GHGs emissions and pollution are not the only problems to face. Another issue is the increase in land use in extending cities, mining, or building infrastructures (highways, railways, airports, harbours). In 2012, the United Nations published a report reporting that urban encroachment increases by 5.5 ha every minute [2]. During the 12th Conference of the Parties (COP) in 2015, the UNCCD secretariat launched

the Land Degradation Neutrality (LDN) program. The goal of this program is to assist countries in achieving neutrality in land degradation¹ targeting 2030 as the horizon. Hence, a tradeoff must be sought between the development of cities (housing, shops, schools, etc.) and land preservation to attain the objectives of the LDN program.

In this work, we explore a scenario in which part of used lands might be re-assigned to new urban projects or allocated for urban greening, with the aim of mitigating the severity of heat waves [3]. According to Adam Millard-Ball, streets right-of-way represent an important percentage of city areas: between 13% and 30% in the US [4] and streets sprawling is still an important feature [5]. Based on these elements, the reduction of urban networks is an attractive approach worth studying. The problem of reducing urban network sprawl by removing lanes of major and/or two-way streets is investigated. Such an operation entails several significant issues. Indeed, for delivery purposes, every location in the city should remain accessible. Additionally, this transformation should be executed in a way that ensures any location in the city remains accessible from any other place. This constraint corresponds to the strong connectivity property of directed graphs. Another concern is the increase in the distance between different locations in the city. Finally, reducing the urban street network may have a notable impact on traffic, an issue not addressed in the current paper but that will be investigated in future work. Based on an argument about cycles in graphs, three algorithms that preserve network strong connectivity are presented. Solutions to the problem consist of two terms, respectively related to the graph structure and to the distances within the graph, leading to a two-objective optimization problem formulation. The first objective is to reduce the number of lanes (one lane corresponds to one arc), while the second is to minimize the increase of the sum of distances for all pairs of locations in the city, which henceforth is referred to as All Pairs Shortest Paths (APSP). It is important to note that both objectives are inversely proportional to each other (i.e., reducing the number of lanes is likely to increase the APSP value). Therefore, the results of the proposed methods are presented as Pareto fronts. The algorithms were applied to several city maps

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¹<https://www2.unccd.int/actions/ldn-target-setting-programme>

obtained from OpenStreetMap. Each city map data has been transformed into a directed graph using GraphStream [6]. The results obtained showed that a substantial number of lanes could be removed from the street network without a major impact on the distances between locations in the city. A comparison between cities is also presented.

The paper is organized into five sections. Section II presents the problem, its characteristics, the model, and related works. The three new proposed algorithms for computing solutions are described and discussed in Section III. Experiments on real city maps are presented in Section IV, and the results are analyzed. Finally some perspectives are drawn in the last Section.

II. MODELS AND RELATED WORKS

A. Models, Constraints, and Objectives

Streets networks can be modeled by different types of graphs [7]. In this work, directed multi-graphs are considered. Nodes represent intersections, junctions, roundabouts, and dead-ends, while arcs represent the streets linking nodes. This corresponds to a primal graph model [8]. Therefore, all one-way streets can be represented as a set of arcs pointing in the same direction, each arc representing one lane. Similarly, every two-way street is represented in the model by two sets of arcs with opposite orientations.

To mitigate the impacts of modifying the street network, the expected methods have to comply with a set of constraints: First, adding new lanes and new streets is prohibited; Second, removing a one-lane street is prohibited; Third, reversing the direction of a lane is prohibited; Finally, fourth, after modification of the network, each location should be reachable from any other location in the city. From a graph theory perspective, each constraint can be reformulated. The first constraint specifies that adding arcs to the graph is not allowed, while the second imposes that if two locations are connected before applying an algorithm, they must remain connected. Thus, if the original streets network is denoted by $G = (V, A)$ and if $G' = (V', A')$ denotes the digraph obtained after applying the method, then $V' = V$, and the neighborhood of any node in G remains unchanged in G' . While the third constraint is straightforward, the last one is much more interesting since it imposes the conservation of the strong connectivity property of the graph.

Two objectives are considered. The first objective is to minimize the number of arcs in the graph while maintaining the strong connectivity constraint such that if two vertices are connected in G , so must they be in G' . The second objective is to minimize the difference in the sum of all pairs of shortest paths (APSP) of nodes between G and G' .

B. Presumption and Related Works

1) *Presumption:* According to the second constraint (wherein removing a one-lane street is not allowed), the only operation that enables the removal of arcs from the graph involves removing one arc from a pair of symmetric arcs. In this work, symmetric arcs are arcs that share the same

endpoints (vertices) but that are oriented in opposite directions: arcs (u, v) and (v, u) constitute symmetric arcs. Another remark concerns multi-graphs. When several arcs of the same length share the same extremities and the same orientation, they can be reduced to only one with no impact on the second objective (APSP). Therefore, this study is concerned with simple directed graphs or 1-digraphs.

2) *Related Work:* The environmental impact is the motivation for this work. The related works can be divided into two main parts, which are the design of urban and the development of an algorithm. Several published works in urban configuration proposed solutions to the environmental problem. The recent work in [9] investigates how to solve a large portion of personal transportation in the US by retrofitting the street network. They investigate the solution to increase pedestrian access to the points of interest in suburban areas. Thus, they can increase the green space by increasing the pedestrian and reducing the use of cars. Theoretical and empirical insights components that impact urban resilience were studied in [10]. The work investigates the design and structure of street and street networks regarding urban resilience. The important components that contribute to the resilience of urban areas were studied in this work. Also, the study in [11] investigates the solutions to reducing the transportation by personal car that causes environmental problems. The possible solution proposed by the work is to increase the travel costs. Thus, people can use alternative transportation, making the urban neighbourhood more appealing. An interesting point for use in this work is that the finding of the effect of the built environment can affect people's travel behaviour. There are several solutions to reduce the environmental problem related to the street network sprawl. Unfortunately, to the best of our knowledge, no works considered removing the street from street network sprawl in the urban study similar to the technical view. Therefore, our work investigates the technique to remove some streets from the street network sprawl. Dealing with strong connectivity is undeniable. The most similar work might be the Strong Orientation Network Problems (SNOP) in [12]. However, the problem addressed in our work does not belong to the family. In most previous works, "the objective is to set an orientation for each edge in an undirected graph such that the resulting digraph is strongly connected and the total travel distance between any pair of nodes is minimized" [13]. In this study, however, the original graph is already strongly connected. The objective, therefore, is concerned with removing arcs while preserving two main characteristics: the neighbourhood of each node and the strong connectivity. This must be accomplished while minimizing the increase in the distance between any pair of nodes in the graph. This formulation represents a significant variation from SNOP-like problems, and state-of-the-art methods applied to SNOP cannot apply to solving the presented problem.

A first method addressing a similar problem was proposed in [14], except that the second objective was the sum of eccentricities instead of the APSP. The method employed an iterative algorithm in which some symmetric arcs were

removed from the graph at each iteration. If the resulting graph was not strongly connected, some removed arcs were restored to recover the property. The sum of eccentricities was then computed, and if the resulting solution was not dominated, it was added to the Pareto front. The experiments were conducted on synthetic graphs, mimicking Manhattan-like urban areas by generating incomplete grids.

Careful consideration of previous works leads to the design of the three new proposed algorithms. The original graph stemmed from the urban street network is strongly connected. Indeed, following lanes, any location in a city can be reached by car from any other location. However, any arc removal may lead to the loss of this property, and its verification for any arc removal operation is time-consuming, as was noted by the authors in [14]. To circumvent this issue, instead of removing arcs individually, a process that identifies a cycle and removes arcs opposite to the cycle provides a guarantee for preserving the strong connectivity property. This observation is exploited to design a generic approach, described in the next section, to address the problem.

III. PROPOSED METHODOLOGY

We denote V_1 as the number of remaining symmetric arcs and V_2 as the All Pairs Shortest Paths (APSP) value. The goal is to minimize both values. However, since minimizing the number of symmetric arcs and minimizing the APSP represent conflicting objectives, the resulting solutions form non-dominated pairs of values denoted as (V_1, V_2) . A pair of values (a, b) is dominated by (a', b') , if and only if a (respectively b) is strictly greater than a' (respectively b') and b (respectively a) is greater or equal to b' (respectively a'). All non-dominated pairs of values constitute the set of non-dominated solutions known as the Pareto front.

A. Generic Algorithm

The general method for generating solutions is mainly based on the last remark of the previous Section, the detection and the choice of cycles for removing symmetric arcs. As illustrated in Figure 1, once a cycle has been chosen, all symmetric arcs with an opposite direction to the cycle are removed from the graph. In the sequel, such arcs are called *opposite symmetric arcs*. Therefore, the approach can be described in its simplest form in Algorithm 1. The three presented algorithms propose variations for the *DetectCycles()* and *ChooseCycles()* functions.

B. The Iterative Depth-First Search Method: I-DFS

This first method uses a classical Depth-First Search (DFS) algorithm for cycle detection. It begins by selecting a vertex at random and marking it as visited. The algorithm proceeds, marking each visited vertex until it revisits a previously marked vertex. When this occurs, it signifies the detection of a cycle. Subsequently, all opposite symmetric arcs are removed, as illustrated in Figure 1. DFS always finds a cycle. However, after a large number of iterations, many arcs have

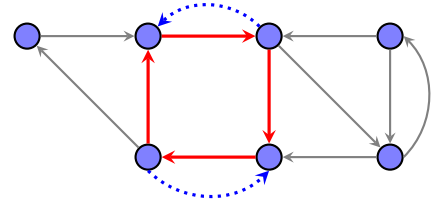


Fig. 1. Principle of Opposite Symmetric Arcs Removal: The arcs of the selected cycle are highlighted in red, and dotted blue lines represent the removed opposite symmetric arcs. This process ensures the preservation of the strong connectivity property.

Algorithm 1: Generic Algorithm

Input: streets network G

```

1 Main():
2    $V_1 \leftarrow$  number of symmetric arcs in  $G$ 
3    $V_2 \leftarrow$  sum of all pairs shortest paths in  $G$ 
4    $S \leftarrow (V_1, V_2)$ 
5   while stop condition not reached do
6      $C \leftarrow$  DetectCycles()
7      $C' \leftarrow$  ChooseCycles( $C$ )
8     RemoveSymmetricArcs( $C'$ )
9      $S \leftarrow$  Update( $V_1, V_2$ )
10    if  $S$  is non-dominated then
11      | add  $S$  to the Pareto front
12    end
13  end
14
```

been removed from the graph, and newly detected cycles may not have opposite symmetric arcs. The stopping condition is determined by a threshold, indicating the number of times the process fails to discover new opposite symmetric arcs.

At present, the algorithm considers only one cycle at a time. It favours the minimization of the number of symmetric arcs, disregarding V_2 , the value of APSP. The following two algorithms attempt to consider two combined cycles for improving both V_1 (number of symmetric arcs) and V_2 values.

C. The Two-Compatible Cycles method: 2CCM

The two-compatible cycles method, 2CCM, still relies on the use of DFS for detecting cycles. However, unlike I-DFS, 2CCM attempts to find pairs of cycles that share common arcs. For this purpose, after detecting one cycle, C_0 , 2CCM proceeds from one vertex of C_0 and attempts to determine a second cycle, C_1 , sharing some arcs with C_0 . The success of finding C_1 is not guaranteed. A threshold T for the maximum number of attempts is set. If, after T tries, no such cycle is found, C_0 is aborted, and a new C_0 cycle is chosen. Conversely, if such a C_1 cycle is found before T attempts, then both cycles are validated, and opposite symmetric arcs of C_0 and C_1 are removed, as illustrated in Figure 2.

The design of this method attempts to minimize the number of symmetric arcs while keeping V_2 as small as possible. Its

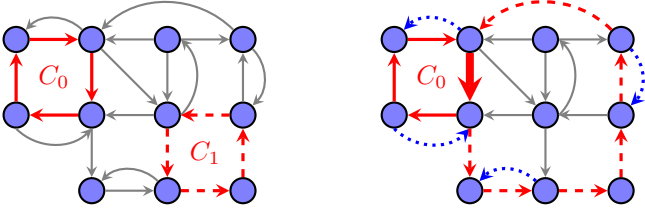


Fig. 2. Principle of Detection of Pairs of Cycles in method 2CCM: Once a first cycle has been detected (C_0), another cycle must be detected starting from a vertex of that cycle. On the left, another cycle has been detected (C_1 , highlighted by dashed arcs). This cycle has no arc in common with C_0 , it is thus invalid for the 2CCM method. On the right, the detected cycle has one common arc with C_0 (the thickened arc), validating the formation of the pair of cycles and leading to the removal of opposite symmetric arcs (dotted arcs) from the two cycles.

main drawback comes from the fact that, after some iterations, the probability of finding such pairs of cycles decreases very significantly. This next proposed algorithm attempts to overcome this drawback and can be considered as a trade-off between I-DFS and 2CCM.

D. The Two-Compatible Cycles with Relaxation Method: 2CCRM

As stated earlier, this proposed algorithm is a trade-off between I-DFS and 2CCM. It is almost the same as the 2CCM method. However, if after T attempts no cycle C_1 , sharing common arcs with C_0 , is found, then only C_0 is validated. Referring to the examples in Figure 2, in both cases, C_0 is chosen by method 2CCRM.

Improving both objectives should be considered and given some priority. 2CCRM is proposed as a trade-off between I-DFS and 2CCM. The following illustrates an example that solutions provided by the three algorithms are complementary for building the Pareto front.

E. Preliminary Observations

In order to demonstrate the distribution of the solutions produced by the three algorithms with a small size of real city map which is Honfleur, France.

The results from the experiment are illustrated in Figure 3. As expected, I-DFS favors the first objective (the minimization of the number of symmetric arcs (V_1 value)), 2CCM produces the best results for the APSP value (V_2), and the relaxed version 2CCRM produces solutions that constitute a trade-off. The Pareto front, illustrated by the thick line on the image, demonstrates the complementarity of the three algorithms. Indeed, the points of the Pareto front belong to the three sets of solutions.

IV. EXPERIMENTS AND ANALYSIS

In experimentation, the global process comprises three steps: (i) Extracting the real city maps data from OpenStreetMap, (ii) Preprocessing the data for building the corresponding graph model, and (iii) Applying the three algorithms to the graph.

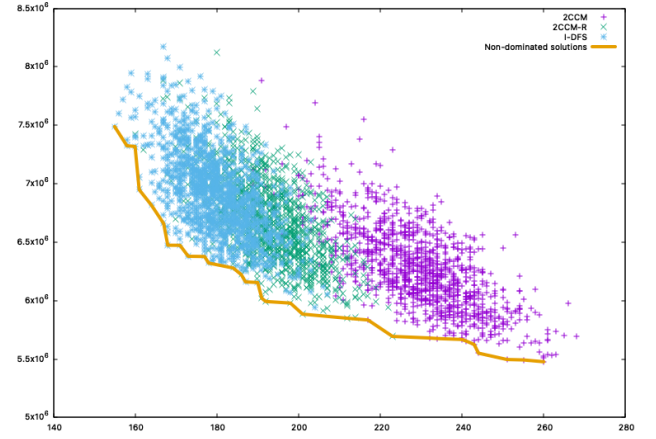


Fig. 3. Solutions from the three algorithms for the Honfleur instance.

A. From Real City Maps to Directed Graphs

Real city map data were extracted from OpenStreetMap (OSM) [15]. Raw data require preprocessing to build the corresponding graph models. Specifically, only drivable streets are selected, as this work focuses on the street network for vehicles. Irrelevant data, such as pedestrian ways and steps, as well as dead-end streets, have been removed during the initial ‘cleansing’ phase. After this preprocessing phase, graph models are built using GraphStream [6], an open-source graph library for modelling graphs. The obtained graph is a directed graph in which the nodes represent junctions, crossroads, and roundabouts, while arcs represent streets. In the city map, some streets may consist of several parallel lanes going in the same direction. In the graph model, one arc per lane should have been considered. However, as discussed in Section II B, when several lanes with the same direction exist between two locations, only one arc is kept in the model.

Verification of the graph’s strong connectivity is necessary. This is done by applying Kosaraju’s algorithm [16]. If the OSM data is restricted to the strict city limits, it may result in a graph that is not strongly connected. Indeed, some city maps cannot be strongly connected by themselves as they have some routes that cross the city’s borders. To address this issue, vertices and arcs located at the borders of the current city with neighbouring ones are added until the resulting graph satisfies the strong connectivity property.

At the end of the process, the graph model for each city map is a strongly connected directed 1-graph. Figure 4 illustrates such a graph for the city of Le Havre (France).

A set of French cities were selected for experimentation. For each city, the graph model was generated according to the method described above. Table I summarizes the main characteristics of these graphs (order and number of arcs) representing the selected cities, as well as the original values of the number of symmetric arcs (V_1 corresponding to the first objective) and of the All Pairs Shortest Paths (V_2 the second objective). The number of arcs ranges from 1025 for

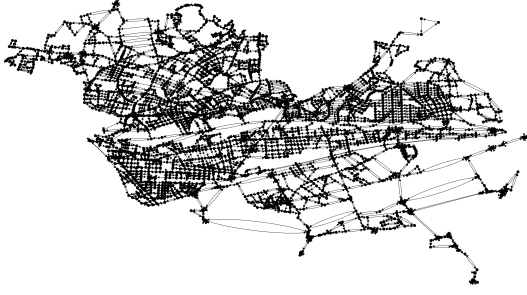


Fig. 4. An example of the Directed Graph Model of Le Havre city (France), obtained from OpenStreetMap and using GraphStream.

the city of Honfleur to 8711 for the city of Limoges. Except for Honfleur, the selection of cities reflects mid-size cities located in different regions with different geographical constraints.

TABLE I
GRAPH CHARACTERISTICS OF A SELECTION OF FRENCH CITIES,
ORDERED BY INCREASING NUMBER OF ARCS.

City	# Arcs	Order	APSP	#Sym.Arc
Honfleur	1025	482	4944246	397
Périgueux	1889	818	17516350	682
Troyes	2736	1231	41842950	936
Bergerac	2853	1236	42749296	1094
Auxerre	2895	1273	41435563	1060
Angoulême	3286	1550	74388525	1048
Valence	3906	1841	114945142	1246
Bourges	5161	2245	196476324	1976
Amiens	5224	2478	218538523	1618
Montauban	5346	2348	174665923	2010
Poitiers	5420	2478	248788279	1851
Saint-Etienne	5550	2414	192083291	1984
Clermont-Ferrand	6210	2825	271354223	2011
Avignon	6916	3264	445990395	2257
Reims	7198	3186	369459703	2418
Le Mans	7333	3235	405449192	2579
Le Havre	7673	3025	333984542	3044
Limoges	8711	3838	612407270	3086

B. Experimentation and solutions

For each city, the three algorithms are applied with 100 iterations. Only non-dominated solutions are kept for building the Pareto Front. In order to facilitate the comparison of solutions from the different pairs cities, the results are normalized. Instead of considering pairs (V_1, V_2) , we consider the percentage of remaining symmetric arcs on the x axis and the percentage of the original APSP value on the y axis are considered. Therefore, values on the x -axis exceed the original 100% (as arcs are removed, this leads to a larger value of APSP). Similarly, values on the y -axis are less than 100%, indicating that the remaining symmetry arcs are less than the original of 100%. Figure 5 depicts the Pareto Fronts for all selected cities.

C. Results Analysis

The first finding results are quite remarkable. It is possible to remove a large percentage of symmetric arcs without a

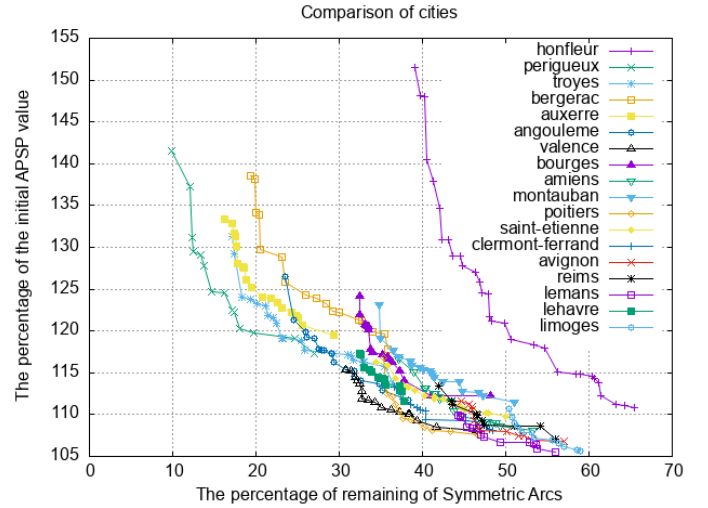


Fig. 5. Pareto fronts for Street Network from cities in France, (Percentage of remaining Symmetric Arcs VS Increase of the APSP value)

significant increase in the value of APSP. On average, when considering our selection of mid-size French cities, it is possible to remove almost 50% of all symmetric arcs for an increase of less than 15% of the value of APSP. In the city of Le Mans, for instance, this means that as many as 1300 lanes can be removed for less than a 10% increase of the APSP.

The second finding concerns the Pareto front for the city of Honfleur, which is significantly different from the others. Removing symmetric arcs seems to be harder for the Honfleur graph than for the other cities. A careful analysis of the graph gives an explanation. It appears that, in the Honfleur Graph, many vertices have only one neighbor vertex, and they are linked by a pair of symmetric arcs. These vertices are highlighted by a circle in Figure 6. In fact, 30% of symmetric arcs cannot be removed without losing the strong connectivity property. In comparison, between 99% and 100% of symmetric arcs in the other city maps can be individually removed without affecting the strong connectivity property.

The third point concerns the observed limit on the maximum number of removed symmetric arcs for each city. Maximum, concerning the proposed algorithms, is likely to be improved by the cooperation of other methods, such as using heuristics. The existence of such a limit is not surprising. In the actual street network, if a small portion of the streets is removed, selecting other routes not too far away can still be possible. However, when many of them are removed, the number of alternative routes decreases significantly, and the alternatives might be much longer than the original path until no alternative route exists between the two locations. This limit is different for each city and may vary a great deal. It is too early at this stage of the current study to conclude anything with certainty. However, this phenomenon might be related to some geographical characteristics or constraints of the city, such as being close to the sea, crossed by a river, etc. Another possibility is that some symmetric arcs play a crucial role,

and their removal limits the possibility of removing other symmetric arcs. But this needs extra investigation to confirm or refute such a claim. We experiment with real-world city maps with different characteristics in the current study state. A few limitations can be improved from this state of work. The efficiency of the algorithms might be one of the keys to improvement by investigating the algorithm that can remove more symmetric arcs by minimizing the total distance. The consideration of the characteristics of the city maps, such as the size of the city or the ratio of the street and the city's surface, can be used as a heuristic in the algorithm.

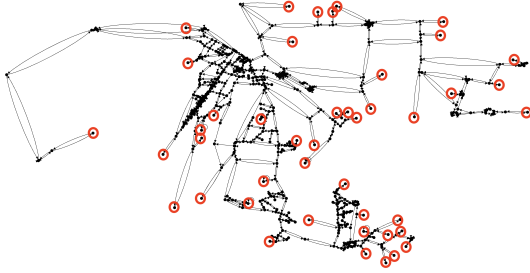


Fig. 6. In the Honfleur Graph, many vertices have only one neighbour with which they are connected with a pair of Symmetric Arcs. Any arc of these pairs cannot be removed without losing the strong connectivity property.

V. CONCLUSION AND PERSPECTIVES

Mitigating the impacts of climate change at the level of cities raises many issues and requires innovative solutions. Reducing the street network space, which represents a significant portion of the urban area, maybe one of them. However, removing streets cannot be done without having a significant impact on the city services unless only some lanes are removed while preserving the whole topological structure of the network and its strong connectivity property. This work is an attempt to achieve such objectives. Formulations and modelling of the problem are discussed as a bi-objective optimization problem (i.e., maximizing the reduction in the number of lanes while minimizing the value of all pairs shortest paths (APSP)), and Pareto Fronts are used to present the solutions. Three algorithms based on cycle detection and removal of opposite symmetric arcs have been proposed. The experimental results, based on real French city maps, reveal that a significant number of symmetric arcs, up to 50% can be removed from a city with a limited impact of less than 15% on the APSP value.

In practice, implementing such a solution in real-world scenario would certainly improve the daily lives of citizens but at the cost of a strong impact on motorized mobility, including cars and public transportation. It should be noted that diverse situations may occur. For instance in mid-sized French cities, shopping centers and supermarkets are located on the outskirts, while in larger European cities many shops are situated downtown. This difference in organization has a

strong impact on the mobility schemes. Thus, as each city has its own mobility patterns, which are influenced by its structure, organization and population behaviors, finding general answers to these issues seems unlikely. Nonetheless, this opens up many interesting perspectives. While some issues like public acceptance is out of the scope of our studies, traffic evolution might be studied through both simulations and the use of other optimization techniques, including metaheuristics. From the dataset perspective, such a study would be extended to cities or various sizes, organization and geographical constraints. In particular, measuring the cross-impact of reducing the street network and the evolution of the number of cars allowed to circulate in the city could provide some insights to guide the future evolution of cities with the aim of mitigating climate change effects.

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