Programming Project II

Routing Algorithm for Ocean Shipping and Urban Deliveries

DA 2023 Instructors Team

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Due Date: May 26, 2023 at midnight (PT time)

1. Objectives

We have seen during the theoretical classes that some problems are *intractable*, that is, there is no efficient solution to solve them. This category of problems is not only academic, as they often show up in realistic real-world applications that require some kind of solution. In the second programming assignment, you will analyse the **Travelling Salesperson Problem (TSP)** and design heuristics to solve it, using several datasets from the context of ocean shipping and urban deliveries.

The goal of this assignment is twofold. First, implement a basic exhaustive approach for the classic routing problem using the TSP abstraction, therefore learning first hand that although such an approach can find optimal solutions, its applicability is restricted to very small graphs. Second, refine your **critical thinking** skills, by developing and analysing a set of approximate solutions to the TSP. You will work in groups of 2 or 3 students (3 is preferable) to encourage interpersonal and project management skills. The deliverables for this project are both a description of an algorithm and its implementation alongside a short presentation.

We next describe the project's motivation, a short overview of the dataset you will work with, the problem statement and the instructions to prepare a presentation and demonstration of your work. The problem statement includes the description of each task (with the corresponding grading). Lastly, we provide specific turn-in instructions you need to follow. **Recall, the deadline is May 26, 2023 at midnight.**

2. Problem Statement

In this programming project, you are asked to design efficient algorithms to find optimal routes for vehicles in generic shipping and delivery scenarios, from urban deliveries to ocean shipping. This problem corresponds to the TSP. As the TSP is intractable, there are no known efficient algorithms to solve it. Backtracking techniques can find the optimal solution to this problem. If the size of the graph is relatively low, the application of these approaches might be reasonable. However, as you will conclude in this project, their application to large graphs is infeasible, due to their high computational complexity. Therefore, approximation algorithms based on heuristics need to be devised to efficiently address TSP-based problems. This class of approaches provide in many cases near-optimal solutions and may also prove bounds on the ratio between the approximate and the optimal solutions.

In this project you are asked to design efficient heuristics for the TSP applied to diverse scenarios. You will be given multiple graphs and a selected departure and arrival point (or node) and assuming (at first) a single vehicle. While you are given plenty of freedom to explore effective heuristics, you are strongly suggested to at least implement the heuristic that takes advantage of a triangular approximation as this one has a guaranteed approximation bound for an important class of graphs. In particular, you should design

appropriate heuristics according to the input data, such as the size and type of the graph, as well as additional information contained in the dataset. In this regard, you should analyse which heuristics are more adequate to a given graph and analyse the trade-offs between optimality and efficiency.

Additionally, you will implement a backtracking algorithm to the TSP. Although this algorithm is not efficient, it will enable you to determine the optimal solution to this problem for small graphs. These results can help you analyse the optimality of your heuristics on small graphs.

3. Problem Data and Basic Interface

To make your problem realistic, you are given several real datasets describing points of delivery in an urban setting as well as harbours in the context of ocean shipping. In addition, the provided data file also contains a set of very small graphs designed to allow you to visually test your algorithmic solutions. These large datasets are derived from realistic settings and are available on Moodle,

To adequately interface with your program, you ought to carry out the following three tasks:

[T1.1: 1.0 point] Create a simple interface menu exposing all the implemented functionalities in a user-friendly interface. This menu will be instrumental to showcase the work you have developed in a short demo to be held at the end of the project.

[T1.2: 1.0 point] Develop basic functionality to load and parse the provided dataset files. This functionality, accessible through the menu, enables the selection of the dataset to be used in the analysis of the algorithms developed. With the extracted information, you must create one (or more) appropriate graphs upon which you will carry out the requested tasks. The modelling of the graph is entirely up to you, as long as it is a sensible representation of the data and enables the correct application of the required algorithms.

[T1.3: 2.0 points] Include documentation for all code implemented in this project, using Doxygen, indicating the corresponding time complexity for each algorithm implemented.

4. Statement of Work

To facilitate your work, we have structured the functionalities you are expected to develop into three sets as follows.

4.1. Backtracking Algorithm [T2.1: 4 points]

In this approach, you are asked to develop a backtracking algorithmic approach to the TSP for a graph starting and ending the node tour on node labelled with the zero-identifier label. You are expected to use the small graphs to validate this approach and to observe that for the larger graphs this approach is not really feasible. To this extent, you are suggested to plot the execution time (or other performance metrics you find significant) to illustrate the feasibility or not of this approach for larger graphs.

4.2. Triangular Approximation Heuristic [T2.2: 4 points]

In this approach, you are asked to use the geographic node data, and implement the approximation algorithm for TSP that relies on the triangular inequality to ensure a 2-approximation algorithm for this problem again starting and ending the node tour on node with the zero-identifier label. You should use the results from this algorithm and compare them with the backtracking algorithm for the same small graphs.

Note: Due to their large size, and potentially storage issues, the real-world graphs are not fully connected. As such, and only whenever you need to determine the distance between two nodes whose edge is not provided, you may use the geographic latitude and longitude distance to determine "on demand" the

distance between two nodes and assume they are therefore connected. You will get a tour that is not "real" in the sense that the edges it is based on do not necessarily exist, but at least you guarantee the 2-approximantion bound. In order to compute the distances between nodes, you need to use the Haversine distance computation described in appendix A.

4.3. Other Heuristics [T2.3: 6 points]

In this approach, you are asked to develop your own "efficient" heuristic for TSP that can leverage, or not, the geographic node data. The emphasis in this approach should be on efficiency as this algorithm should be feasible even for the large graphs. Here you can make use of several algorithmic techniques from the use of divide-and-conquer to split the graph into multiple geographic sections to the use of clustering, or both, possibly even in combination with the 2-approximation algorithm. Note though, that in this algorithm the tour has to rely exclusively on "real" or existing edges and cannot be "approximated" as you possibly have done in the 2-approximation algorithm. Nevertheless, you may use the "non-real" approximation solution as a basis for your heuristic.

In the end, you are strongly suggested to compare the quality and run-time performance of your heuristic solution against the 2-approximation algorithm (if you do not rely on it). Although possible, you are not expected to present multiple heuristics, but rather an heuristic that works well over the basic 2-approximation or one that offers comparable tour length results but with noticeably faster execution time (*i.e.*, time complexity). You should avoid investing a tremendous effort in developing an heuristic that yields marginal gains.

5. Demonstration & Presentation

Giving a presentation that is "short-and-to-the point" is increasingly important. As such, you are required to structure a short 15-minute presentation of your work, where you can highlight the most important aspects of your implementation.

> **[T4.1: 2.0 points]** Prepare a presentation of your work with the main conclusions about your implementation of the TSP applied to the scenario of urban deliveries. Your presentation should focus on the explanation and analysis of the heuristics developed for the graphs represented in the dataset, using illustrative examples. In addition to the rationale of your heuristics, you should discuss which heuristics are more adequate to a given graph in the dataset. In this discussion, you should also analyse the trade-offs between the efficiency and the optimality of your solution for all graphs provided in the datasets. The optimality of your heuristics can be analysed by comparing their results with the results produced by the backtracking algorithm. In addition to the heuristics, your presentation should also explain the implemented backtracking algorithm for the toy example graphs.

6. The Dataset

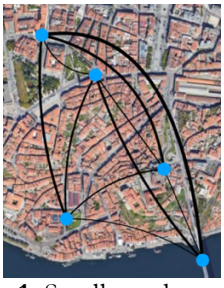
Unlike the first programming project, where you were given a dataset and your goal was to build a solution tailored to that dataset, in this second project the emphasis is on the algorithmic techniques and your interpretation of their outcomes. As such, you are given 6 graphs: 3 graphs are **toy examples**, the other three are scaled-down version of real graphs generated from instances of real urban delivery datasets.

6.1. Toy Graph Examples

You are given three different small graphs, where backtracking strategies are feasible, allowing you to determine ground truth for the solution and benchmark your heuristics. Note that the performance of your heuristics in the toy examples are not generalizable to the real-world datasets. Instead, these toy examples are given to support the development of your heuristics to have some degree of assurance that they are behaving as you expect them to.

The data is represented in different ways for the small and large graphs. The small graphs are described by a single file using a comma-separated values (csv) data format with nodes indicated by a numeric integer index (starting at 0) and explicitly listing all the edges as shown below. In this particular case, a small set of touristic interest points in the city of Porto are listed with an illustrative distance between them. An optional label column is also included which you can safely ignore.

Recall that these small, toy-example graphs, are aimed at being used for validation of the backtracking algorithms as they have no geographic coordinates. You may use them for validation purposes only. Also, as you can observe, in some cases the graphs are missing edges between nodes, i.e., they are not fully connected. This is perfectly normal as some routes or segments between nodes are to be discouraged and can therefore be assumed as infinite.



A	B	C	D	E
origem	destino	distancia	label origem	label destino
0	1	1300	carmo	dLuis
0	2	1000	carmo	se
0	3	450	carmo	clerigos
0	4	750	carmo	bolsa
1	2	450	dLuis	se
1	3	950	dLuis	clerigos
1	4	450	dLuis	bolsa
2	3	500	se	clerigos
2	4	600	se	bolsa
3	4	750	clerigos	bolsa

Fig. 1. Small graph example for points of interest in the city of Porto.

6.2. Real-World Graphs

For the larger 3 graphs, the representation includes two files, one named edges.csv, which lists the nodes along their geographic coordinates (in terms of longitude and latitude) and a second file, named edges.csv, that lists all the edges (assumed to be undirected) as a pair source-destination associated with the corresponding distance. A sample of a tiny portion of the edges.csv file and nodes.csv file is shown below. Notice that your heuristic approach **must ignore** for the purposes of defining a real tour the geographic information as the distances are already included for every existing edge and so rely only on the edge. You may, nevertheless, use the geographic information for other purposes, such as for graph partitioning or node clustering as possible heuristic techniques.

id	longitude	latitude
0	-47.84923	-15.6743
1	-47.654252	-15.601082
2	-47.812892	-15.649247
3	-47.828528	-15.675495

origem	destino	distancia
0	1	25793.4
0	2	9851.6
0	3	7216.7
0	4	26900.9

Fig. 2. Sample of large graph files (nodes.csv on the left and edges.csv on the right).

Regarding the 3 real-world graphs in this dataset we have the following edge and node statistics:

- Graph 1 has 1K nodes and ~500K edges
- Graph 2 has 5K nodes and ~3M edges
- Graph 3 has 10K nodes and ~10M edges

6.3. Extra Medium-Size Graphs

These 12 medium-size and fully connected graphs have between 25 and 900 nodes you can experiment with for the various algorithmic solutions Unlike the real-world graphs, each of these graphs is represented

exclusively by the edges so the number of nodes is included in the file name (edges_25.csv means the graph has 25 nodes).

7. Turn-In Instructions & Deadline

Submit a zip file named DA2023_PRJ2_G<GN>.zip on Moodle, where GN stands for your group number (e.g., 01_2), with the following content:

- Code folder, containing the program source code, but without compilation artefacts.
- Documentation folder, containing HTML documentation, generated using Doxygen.
- Presentation file (PDF format) that will serve as a basis for the demonstration.

Late submissions, up to 24 hours and 48 hours, will incur a penalty of 10% and 25% of the grade, respectively. No submissions will be accepted 48 hours after the deadline. Exceptions apply for justified and documented technical submissions issues. **Recall, the deadline is May 26, 2023 at midnight.**

Appendix A – Haversine Distance

General description in: https://en.wikipedia.org/wiki/Haversine_formula

C++ implementation: https://github.com/AhiyaHiya/haversine
Python: https://github.com/scikit-mobility/scikit-mobility/blob/master/skmob/utils/gislib.py

Pseudo-code using the atan function: (atan2 https://cplusplus.com/reference/cmath/atan2/)

```
convert_to_radians(coord):
   return coord*pi/180

Haversine([lat1, lon1], [lat2, lon2]):

   rad_lat1, rad_lon1, rad_lat2, rad_lon2 = convert_to_radians(lat1), convert_to_radians(lon1),
convert_to_radians(lat2), convert_to_radians(lon2)

   delta_lat = rad_lat2 - rad_lat1
   delta_lon = rad_lon2 - rad_lon1

   aux = sin^2(delta_lat/2)  +  cos(rad_lat1) * cos(rad_lat2)  *  sin^2(delta_lon/2)
   c = 2.0 * atan2 ( sqrt(a),  sqrt(1.0-a))
   earthradius = 6371000 (in meters)
   return earthradius * c
```