INFO 6205 Spring 2023 Project

Traveling Salesman Problem Solution Using Christofides Algorithm and other optimization techniques

By:

Chandan Anandachari - 002777668

Natarajan Lekshmi Narayana Pillai - 002766033

Chaman Betrabet - 002784662

Aim:

The aim of this report is to investigate the effectiveness of the Christofides algorithm and its optimization methods, including tactical methods such as random swapping and 2-opt improvement, and strategic methods such as simulated annealing and ant colony optimization. Using these methods, we can obtain high-quality approximate solutions to the traveling salesman problem. This report will also explore the limitations and challenges associated with these methods and provide recommendations for future research in this area.

Approach:

We used IntelliJ IDE to develop a Java program to accomplish the aim of this report. The program was designed to implement the Christofides algorithm and optimize it using tactical and strategic methods. To increase modularity, reusability and readability of the program, we use Object-Oriented Programming (OOP) concepts.

The development of the program happened in several stages. First, we designed the data structures and classes necessary to implement the algorithm, such as Vertex, Edge and Data. Next, we implemented the Christofides algorithm and the optimization methods, including random swapping, 2-opt improvement, simulated annealing, and ant colony optimization. We also developed invariants to make sure the algorithm and its results are accurate.

To test the above algorithms we use a kaggle dataset, which had IDs, latitude and longitude values. From there we calculated the distance using the Haversine formula, and then we used Prims algorithm to derive the MST Value to find out the odd vertices. Using perfect matching algorithm, we match the edges, so that they form the minimum value. After that, the cycle is discovered by using the eulerian graph and cycle, and Hamiltonian cycle to remove redundant vertices. This tour was then forwarded to random swap, 2-opt, simulated annealing and ant colony. With the help of these algorithms, we were able to find the optimal tour value.

We analyzed the program's results and used graphical representations to illustrate the program's accuracy and performance.

Overall, the approach we used in this report combined theoretical analysis, programming, and experimentation to achieve the aim of investigating the effectiveness of the Christofides algorithm and its optimization methods in obtaining high-quality approximate solutions to the traveling salesman problem.

Program:

Data Structures used :

- Lists
- HashMaps
- Customized classes (Data, Vertex and Edges)

Classes used :

- Edge: used to store the vertex v1 and vertex v2
- Eulerian Circuit: Used to calculate the eulerian graph and cycle
- Hungarian: Used to calculate the value of minimum cost edges among the odd vertices
- Odd Vertices: Used to calculate the odd vertices in MST
- Prims: Used to calculate the Minimum Spanning Tree
- Ant Colony: Will help in determining the optimized value using the hamiltonian circuit.
- RandomSwap:Used to calculate the optimized value using random swap algorithm.
- TwoOpt: Used to calculate the tour and optimizing the tour length.
- Simulated Annealing: used to calculate the value of the optimized tour.
- CostTraversal: Used to calculate the cost of the entire tour traversal.
- Haversine Distance: Used to calculate the distance between two longitude and latitude
- ReadingData: Used to read values from the csv file.
- MapPanel: Used to plot out the vertices and the edges
- TSP_GUI: Used to add the panel and buttons into a single frame
- Vertex: Used to send the X, Y coordinate and IDs
- ExecutorMain: Used to execute the main function and all the other optimized values.

Algorithm used:

Christofides:

The Christofides algorithm is a heuristic algorithm that provides an approximate solution to the traveling salesman problem.

The process by which it works is by

1. Finding a minimum spanning tree
2. Creating a subgraph of odd degree vertices
3. Finding a minimum weight perfect matching
4. Combining the minimum spanning tree and the perfect matching that includes all vertices with an even degree
5. Finding an Eulerian circuit (traversing each edge of the graph exactly once)
6. Transforming it into a Hamiltonian circuit (traversing each vertex of the graph exactly once by skipping previously visited vertices)

This algorithm guarantees that the solution will be at most 1.5 times the optimal solution, with a time complexity of $O(N^2 \log(N))$ for a graph with N vertices.

Random Swapping:

This method of tactical optimization involves randomly switching the order of two cities (vertices) in the solution to see whether it improves it. It is a straightforward strategy that has the potential to enhance the solution but also runs the risk of becoming caught in local optima since the algorithm only explores the neighboring solution by swapping two cities.

2-Opt:

This tactical optimization method involves removing two edges from the solution and reconnecting them in a different way, checking if it results in a better solution. It can be more effective in improving the solution, but is more computationally expensive than random swapping.

Simulated Annealing:

The metaheuristic algorithm for strategic optimization is based on the annealing process in metallurgy. It starts with a high temperature and gradually cools down the system, allowing for more exploration at the beginning and more exploitation at the end. It can be useful in finding local optima, but careful parameter adjustment is necessary.

Ant Colony:

This strategic optimization method is based on the swarm intelligence of ants, who use pheromone trails to locate the shortest route between their nest and a food source. By laying virtual pheromone trails on the graph, the algorithm employs a similar method to determine the shortest path. It can be effective in finding good solutions quickly but require careful tuning of its parameters and can get stuck in local optima.

Invariants:

The graph must be undirected and connected

The minimum spanning tree must be connected

The subgraph of odd degree vertices must have an even number of vertices

The edges in the minimum weight perfect matching must connect odd degree vertices

The combined graph must have even degree vertices

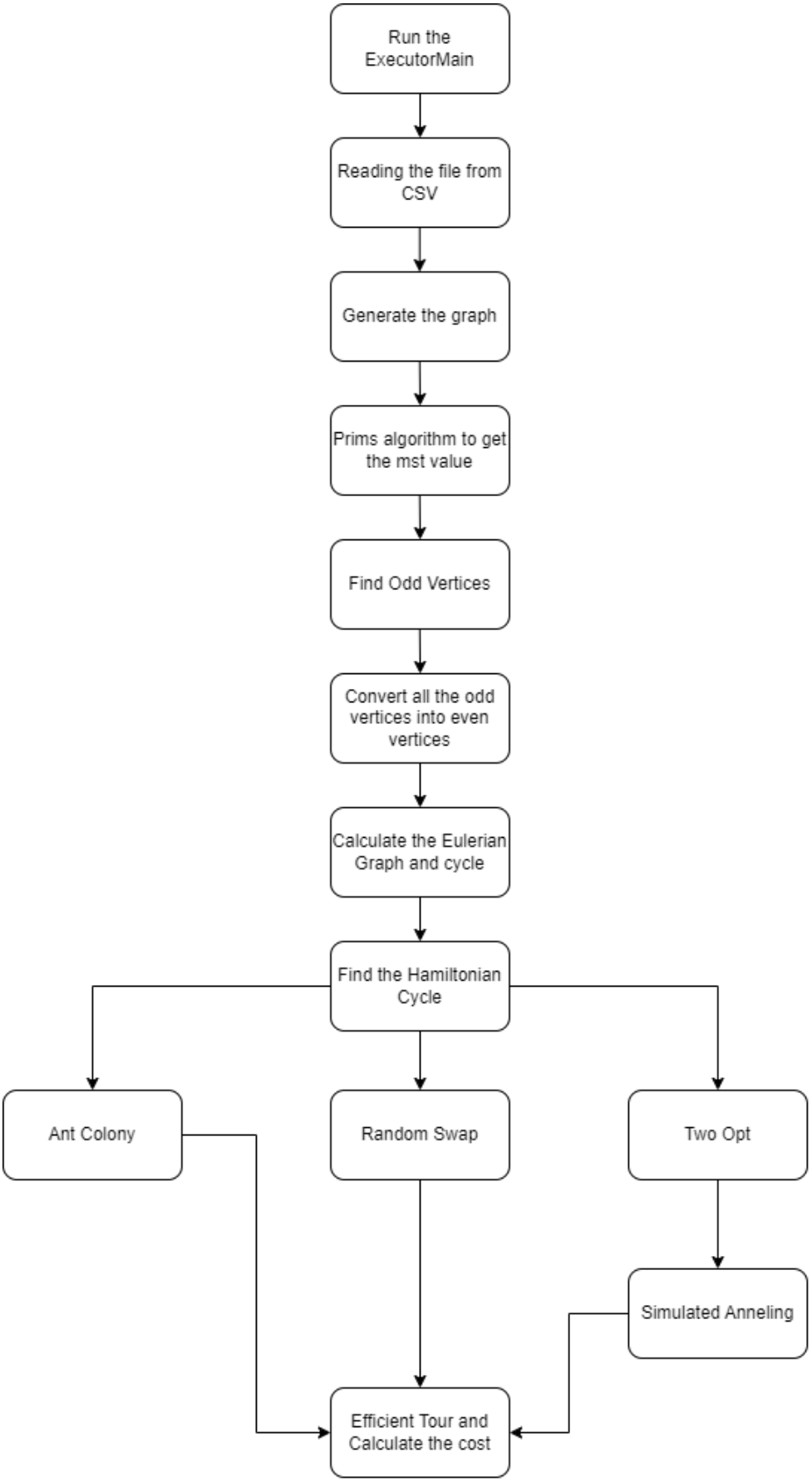
The Eulerian circuit must start and end at the same vertex

Throughout the program, the edges, which are produced by the primality methods used to calculate the Minimum Spanning Tree, will have the same value.

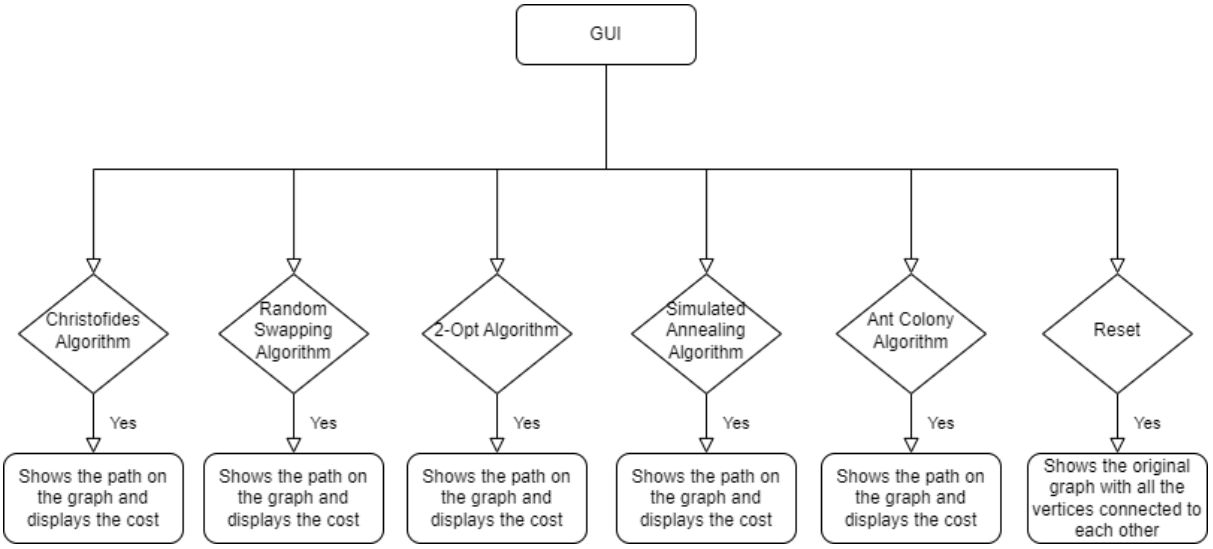
The data that is read from the dataset is moved to the list of type data that is used by the UI to identify the vertices.

Every tour is recorded in a separate list so that it may be used to determine the traversal cost and fed to other algorithms to get the most efficient value.

Flow Chart (Algorithms):



Flow Chart (GUI):



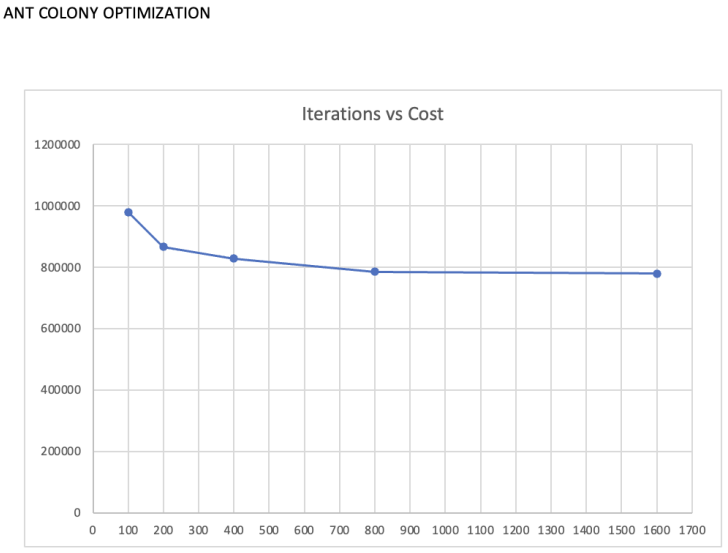
Observations and Graphical Analysis:

Ant colony optimization: We have done our benchmarking for the Ant Colony Optimization, by varying the no. of iterations. We have given the value of the parameters for the formula as follows:

- Alpha (α) – Alpha determines the weight, or priority given to the pheromone trail while the ant chooses the next city. In our benchmarks, we have given a value of 1.0 to alpha
- Beta (β) – Beta determines the weight, or priority given to the heuristic information while the ant chooses the next city. In our benchmarks, we have given a value of 5.0 to beta
- Evaporation is the rate at which the pheromone trail evaporates over time. This parameter is used to avoid the pheromone trail from being too strong and dominating the decision of the ants, leading to suboptimal solutions. A higher value of evaporation means that the pheromone trail evaporates faster. We have given a value of 0.5 for evaporation.
- Q is a parameter that controls the amount of pheromone that an ant deposits on the path. A higher value of Q means that more pheromone is deposited on the path. We have given a value of 500 for Q.

Find below the graph and data showing variation of cost over iterations:

Iterations	Cost (in metres)
100	979331.14
200	866057.22
400	828477.6
800	784752.82
1600	778879.81



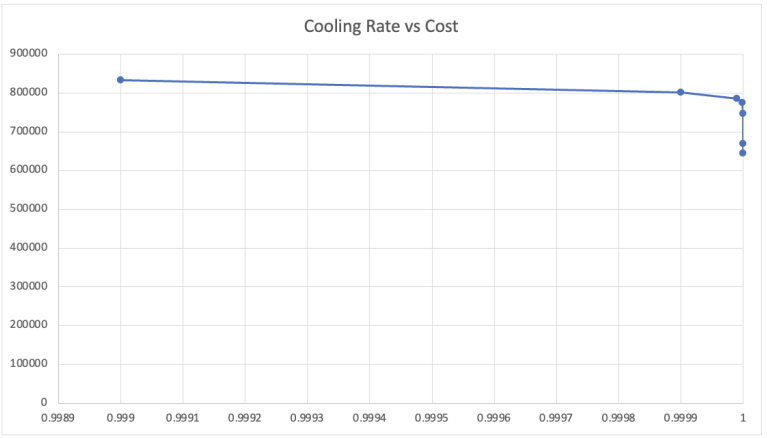
From this, we notice that as we increase the number of iterations, the cost becomes more optimal.

Simulated annealing: For simulated annealing optimization, we have done the benchmarking by varying the cooling rate.

Please find below the data and the graph showing variation of cost over cooling rate:

SIMULATED ANNEALING

Cooling Rate	Cost (in metres)
0.999	833668.481
0.9999	801283.387
0.99999	785765.367
0.999999	774876.974
0.9999999	746160.752
0.99999999	669103.14
0.999999999	643752.481



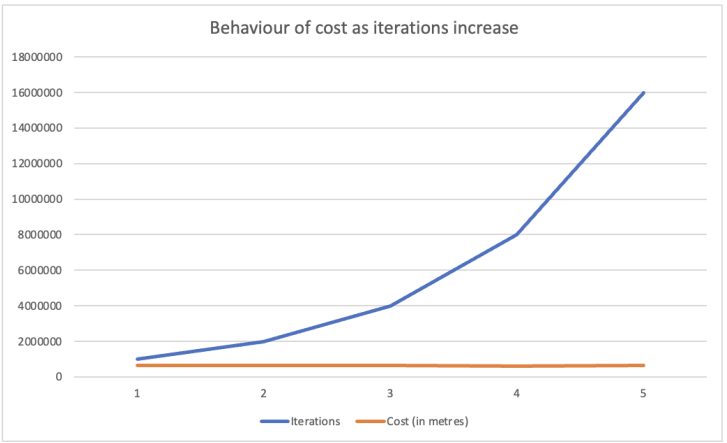
From this, we notice as we increase the accuracy of the cooling rate, we get a more optimal cost solution in metres.

2 Opt: For 2 Opt optimization techniques, the cost remains constant as the no. of iterations increase. The time complexity for this algorithm is $O(n^2)$.

Please find below the data and and the graph showing variation of iterations over cost:

2 OPT

Iterations	Cost (in metres)
1000000	655773.28
2000000	656864.49
4000000	655746.11
8000000	655543.72
16000000	658925.89



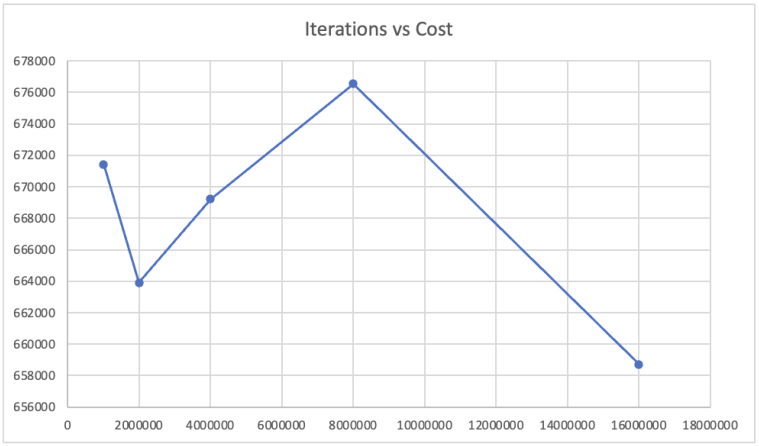
From the data and graph, we notice that as no. of iterations increase, the cost remains constant.

Random swap: For random swap optimization technique, the cost varies slightly over the number of iterations. This is because this technique is randomly swapping two edges and calculating the vertex length adding on to the cost.

Please find below the data and graph for the same:

RANDOM SWAPPING

Iterations	Cost (in metres)
1000000	671432.57
2000000	663891.22
4000000	669215.49
8000000	676543.88
16000000	658719.36



Results and Mathematical Analysis:

We have used a few mathematical formulas for the various algorithms we have implemented. These are explained below:

Haversine formula: We have used the Haversine formula to calculate the distance between the edges of the input file to generate the distance matrix. The Haversine formula is a mathematical formula used in navigation to calculate the distance between two points on the surface of a sphere, such as the Earth. It is commonly used to calculate the distance between two locations given their latitudes and longitudes. The Haversine formula is derived from the law of haversines, which states that for a triangle on the surface of a sphere, the haversine of each angle is equal to the haversine of the sum of the other two angles minus the product of the haversines of those angles. The formula uses the arcsin function to calculate the angle between the two points, and the trigonometric functions sin and cos to convert the latitudes and longitudes to angles. The formula assumes that the Earth is a perfect sphere, which is not entirely accurate, but is generally considered to be accurate enough for most applications.

The Haversine formula is given by:
d = 2r arcsin(sqrt(sin^2((lat2-lat1)/2) + cos(lat1) * cos(lat2) * sin^2((lon2-lon1)/2)))
where:
d is the distance between the two points (in the same units as r, typically kilometers or miles)
r is the radius of the sphere (in the same units as d)
lat1 and lat2 are the latitudes of the two points (in degrees)
lon1 and lon2 are the longitudes of the two points (in degrees)

Simulated Annealing: One of the optimization techniques we have used to get the optimum TSP solution is Simulated Annealing.

In simulated annealing, the algorithm starts with an initial solution and iteratively generates new candidate solutions by making small random changes to the current solution. The algorithm then evaluates the objective function for each candidate solution and decides whether to accept or reject the new solution based on a probability distribution.

The Metropolis-Hastings algorithm determines the probability distribution for simulated annealing, which is based on the difference between the objective function values of the current and alternative solutions as well as a temperature parameter that drops over time in accordance with a cooling schedule. The cooling schedule is often created to strike a balance between exploration (looking for new solutions) and exploitation (using the existing solution to its fullest extent).

P(x',x,k,T) = exp[-(f(x') - f(x))/(kT)] is the mathematical formula for the acceptance probability of a candidate solution with objective function value f(x) and temperature T at iteration k.
where T is the current temperature, k is a constant, x is the current solution, and x' is the potential solution.

Ant Colony Optimization: One of the optimization techniques we have used to get the optimum TSP solution is the Ant Colony Optimization technique.

The pheromone trail levels for each edge in the graph are calculated as part of the ACO algorithm and updated based on the effectiveness of the ants' solutions. The pheromone level and a heuristic value, which indicates the edge's desirability based on parameters like its length or cost, are then combined to estimate the likelihood that an ant will choose a certain edge.

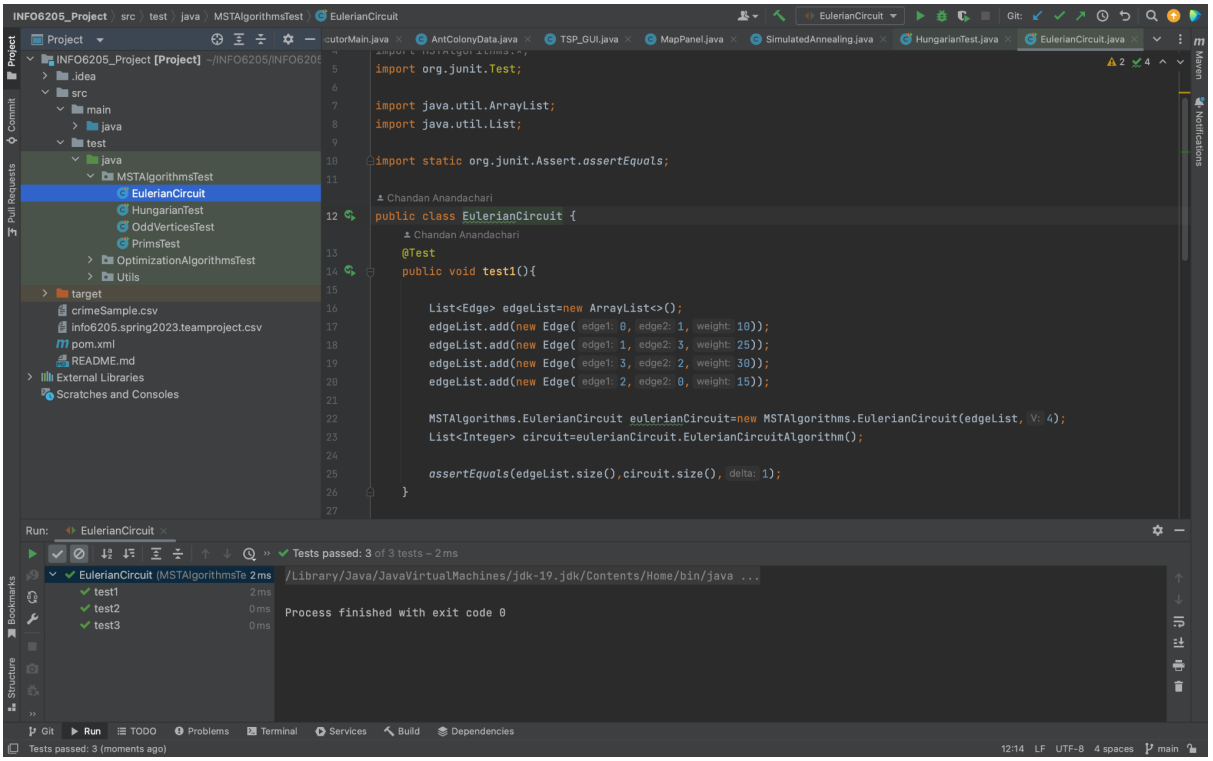
The formula appears as follows:

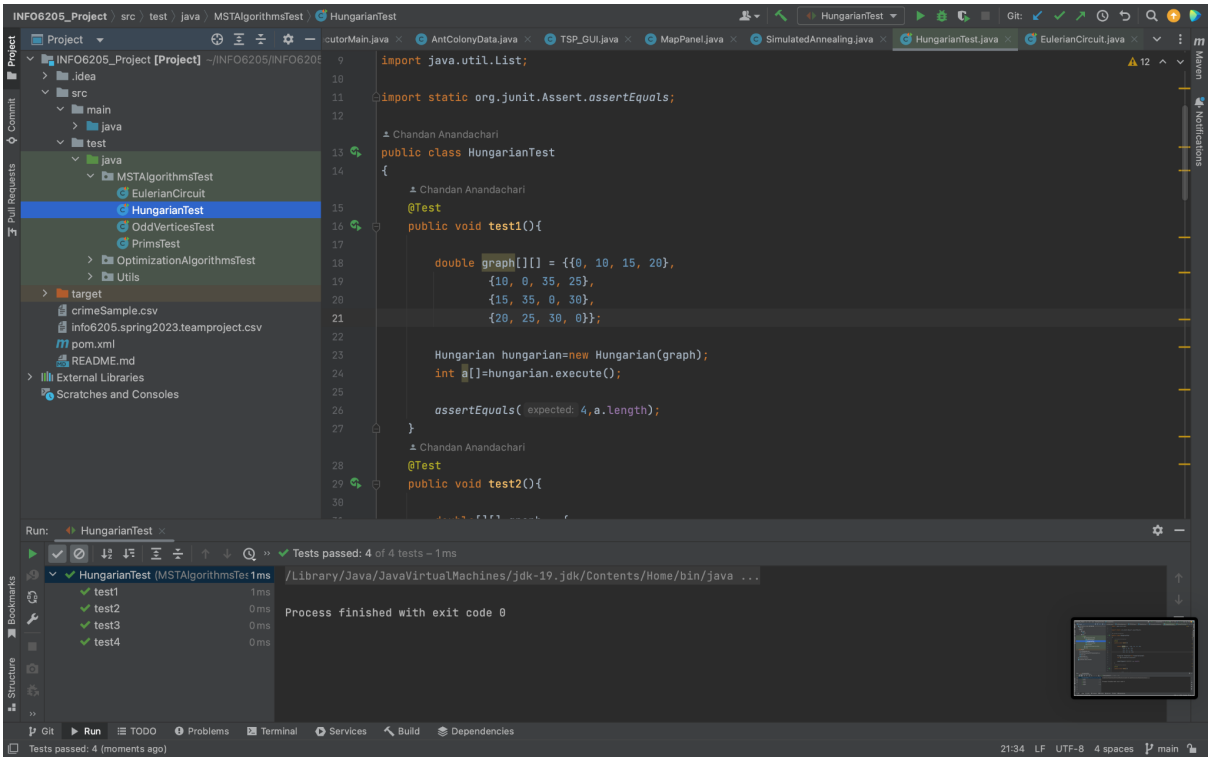
p(i,j) is equal to [(i,j) (i,j)] / [(i,k) (i,k)].

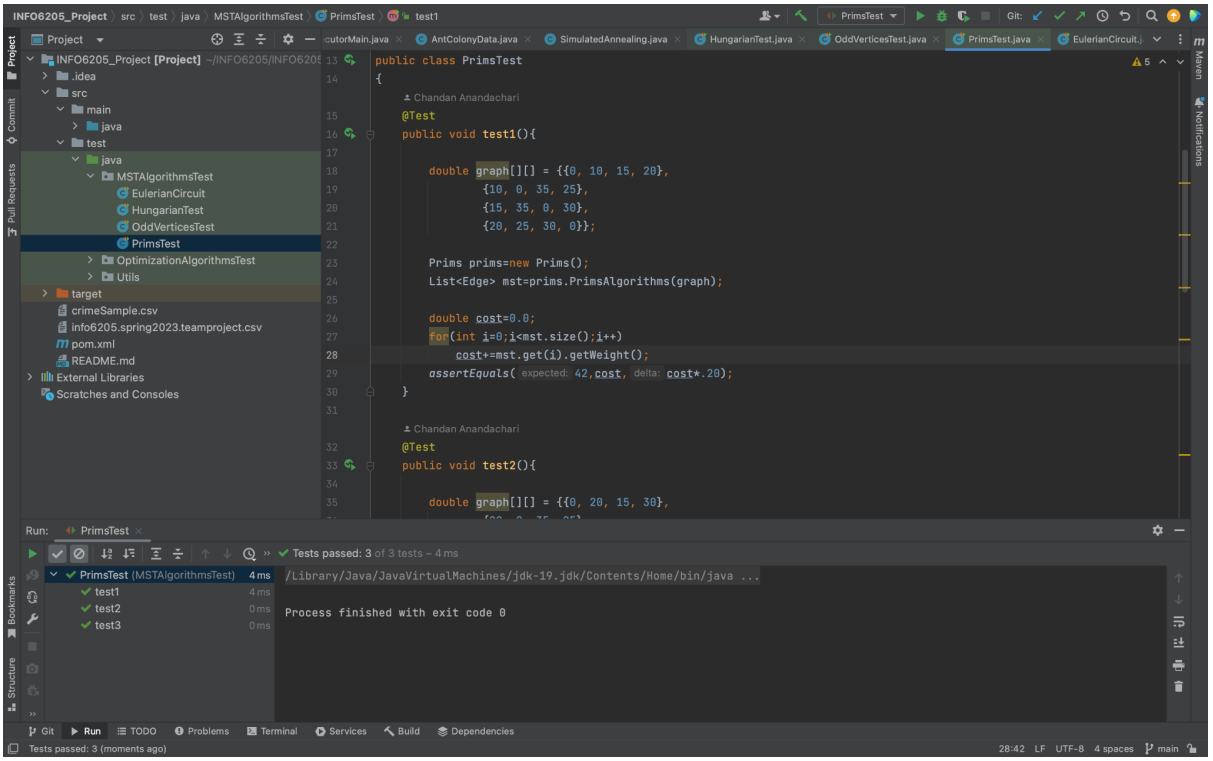
where p(i,j) is the likelihood that an ant would move from node i to node j, (i,j) is the pheromone level on that edge, (i,j) is the edge's heuristic value, and and are parameters that regulate the relative weights of the pheromone and heuristic values, respectively. The probability of all the edges leaving node i are totaled in the denominator.

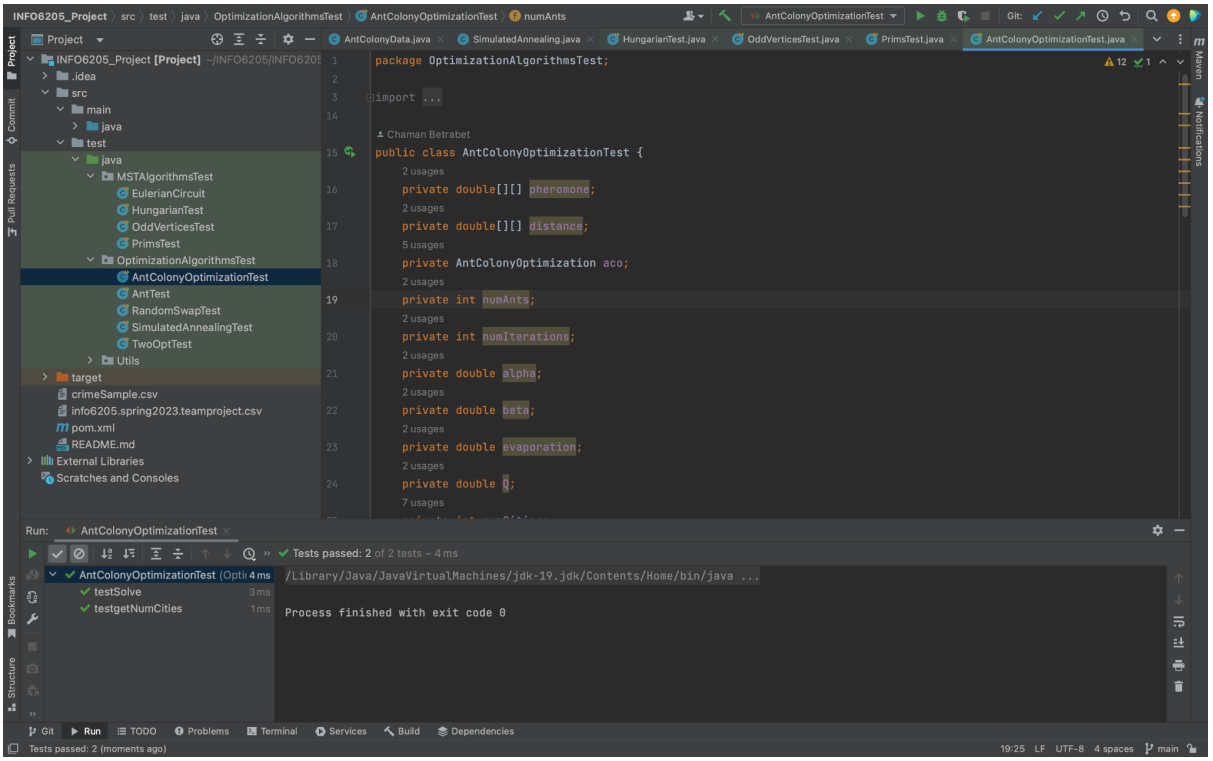
Prims' Algorithm is used for finding out the MST (Minimum spanning tree).
We have used the Hungarian Algorithm to calculate the minimum weight perfect matching.
Christofides algorithm is used to solve TSP.
2 opt and random swap are optimizations we have used to get the most optimal solution for the TSP.
Note: For optimization techniques like Ant Colony Optimization and Simulated Annealing, since the complexity is dependent on input parameters, it is tough to determine the exact time complexity.

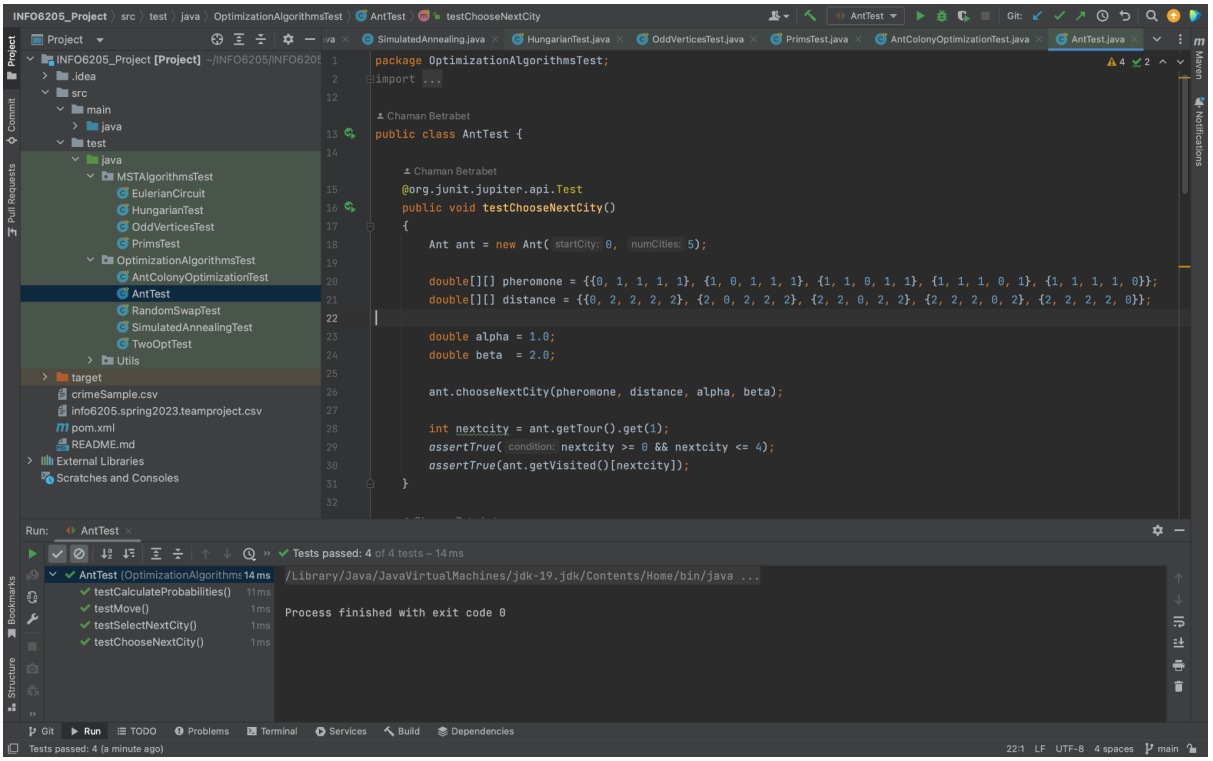
Unit Test:

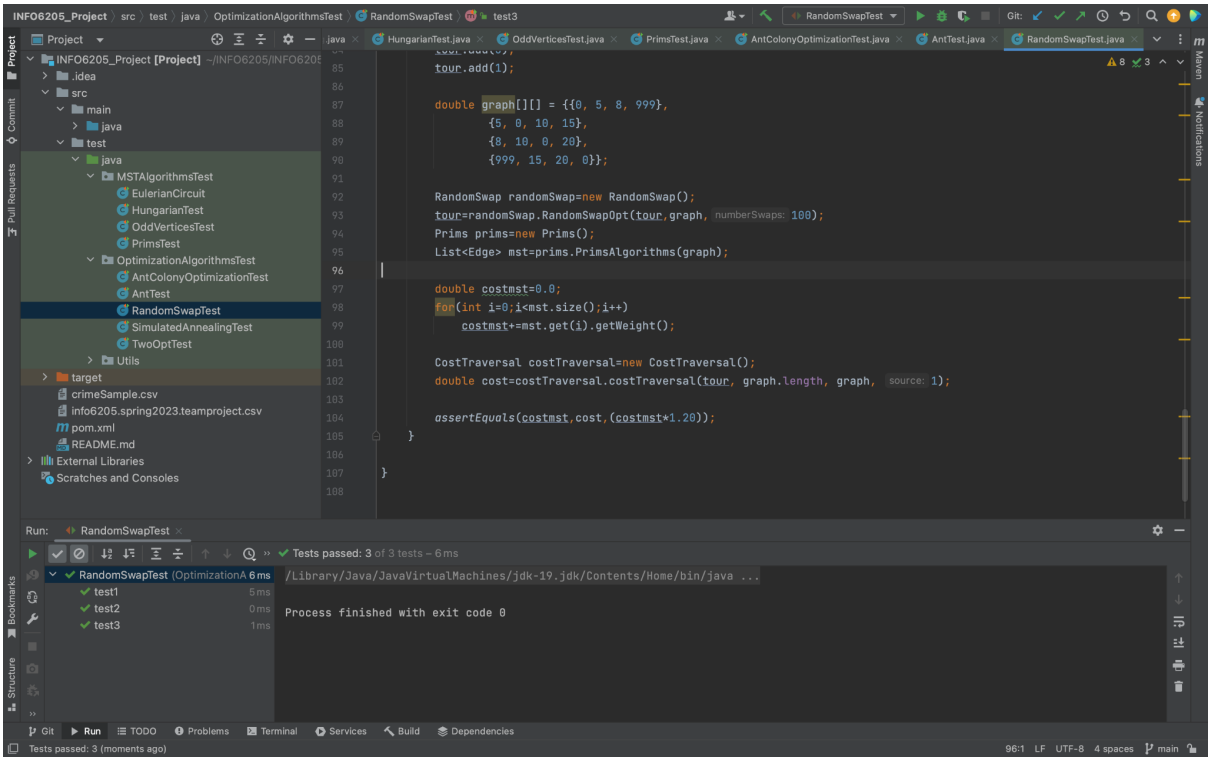

INFO6205_Project
src
test
java
MSTAlgorithmsTest
EulerianCircuit
import org.junit.Test;
import java.util.ArrayList;
import java.util.List;
import static org.junit.Assert.assertEquals;
Chandan Anandachari
public class EulerianCircuit {
@Test
public void test1(){
List<Edge> edgeList=new ArrayList<>();
edgeList.add(new Edge(edge1: 0, edge2: 1, weight: 10));
edgeList.add(new Edge(edge1: 1, edge2: 3, weight: 25));
edgeList.add(new Edge(edge1: 3, edge2: 2, weight: 30));
edgeList.add(new Edge(edge1: 2, edge2: 0, weight: 15));
MSTAlgorithms.EulerianCircuit eulerianCircuit=new MSTAlgorithms.EulerianCircuit(edgeList, V: 4);
List<Integer> circuit=eulerianCircuit.EulerianCircuitAlgorithm();
assertEquals(edgeList.size(),circuit.size(), delta: 1);
}
Run: EulerianCircuit
Tests passed: 3 of 3 tests – 2 ms
EulerianCircuit (MSTAlgorithmsTe 2 ms
test1 2 ms
test2 0 ms
test3 0 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 3 (moments ago)
12:14
LF
UTF-8
4 spaces
main

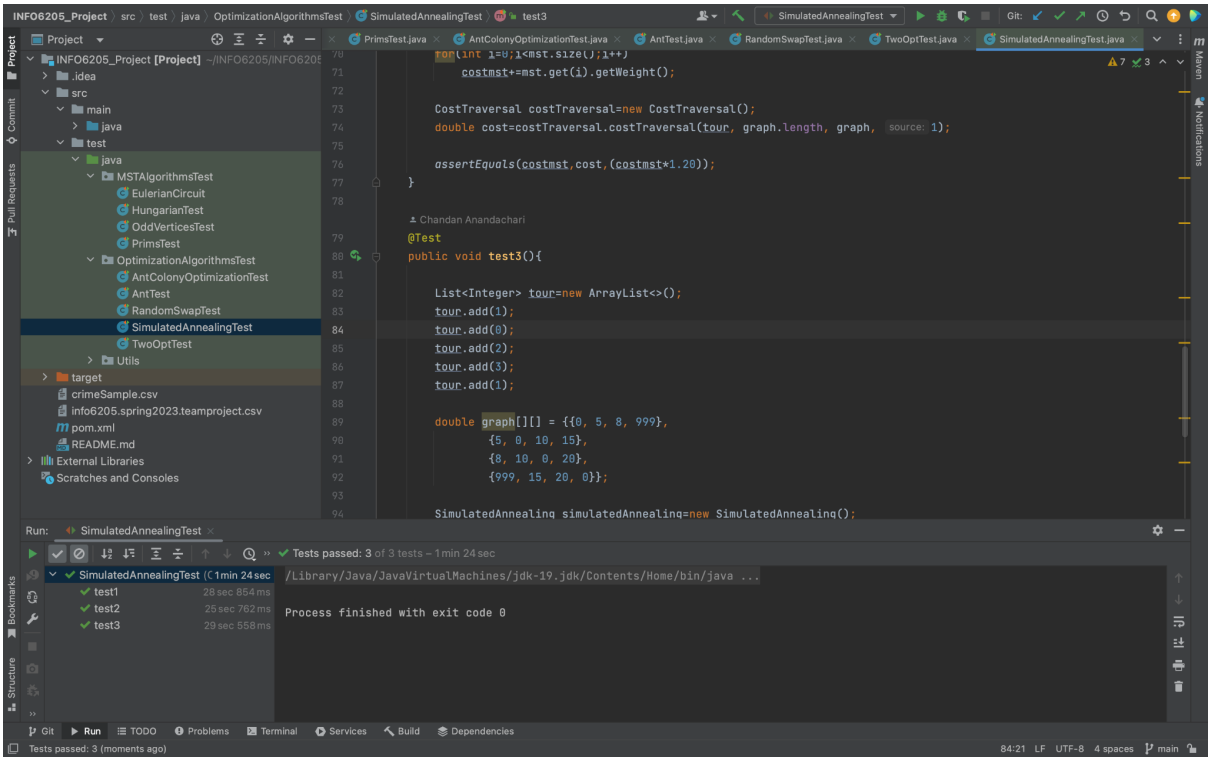

INFO6205_Project
src
test
java
MSTAlgorithmsTest
HungarianTest
import java.util.List;
import static org.junit.Assert.assertEquals;
Chandan Anandachari
public class HungarianTest
{
@Test
public void test1(){
double graph[][] = {{0, 10, 15, 20},
{10, 0, 35, 25},
{15, 35, 0, 30},
{20, 25, 30, 0}};
Hungarian hungarian=new Hungarian(graph);
int a[]=hungarian.execute();
assertEquals(expected: 4,a.length);
}
@Test
public void test2(){
Run: HungarianTest
Tests passed: 4 of 4 tests – 1 ms
HungarianTest (MSTAlgorithmsTes 1 ms
test1 1 ms
test2 0 ms
test3 0 ms
test4 0 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 4 (moments ago)
21:34
LF
UTF-8
4 spaces
main


INFO6205_Project
src
test
java
MSTAlgorithmsTest
PrimsTest
test1
PrimsTest
Git:
Project
AntColonyData.java
SimulatedAnnealing.java
HungarianTest.java
OddVerticesTest.java
PrimsTest.java
EulerianCircuit.j
INFO6205_Project [Project] ~/INFO6205/INFO6205
.idea
src
main
java
test
java
MSTAlgorithmsTest
EulerianCircuit
HungarianTest
OddVerticesTest
PrimsTest
OptimizationAlgorithmsTest
Utils
target
crimeSample.csv
info6205.spring2023.teamproject.csv
pom.xml
README.md
External Libraries
Scratches and Consoles
public class PrimsTest
{
Chandan Anandachari
@Test
public void test1(){
double graph[][] = {{0, 10, 15, 20},
{10, 0, 35, 25},
{15, 35, 0, 30},
{20, 25, 30, 0}};
Prims prims=new Prims();
List<Edge> mst=prims.PrimsAlgorithms(graph);
double cost=0.0;
for(int i=0;i<mst.size();i++)
cost+=mst.get(i).getWeight();
assertEquals(expected: 42,cost, delta: cost*.20);
}
Chandan Anandachari
@Test
public void test2(){
double graph[][] = {{0, 20, 15, 30},
Run:
PrimsTest
Tests passed: 3 of 3 tests – 4 ms
PrimsTest (MSTAlgorithmsTest) 4 ms
test1 4 ms
test2 0 ms
test3 0 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 3 (moments ago)
28:42
LF
UTF-8
4 spaces
main


INFO6205_Project
src
test
java
OptimizationAlgorithmsTest
AntColonyOptimizationTest
numAnts
AntColonyOptimizationTest
Git:
Project
AntColonyData.java
SimulatedAnnealing.java
HungarianTest.java
OddVerticesTest.java
PrimsTest.java
AntColonyOptimizationTest.java
INFO6205_Project [Project] ~/INFO6205/INFO6205
.idea
src
main
java
test
java
MSTAlgorithmsTest
EulerianCircuit
HungarianTest
OddVerticesTest
PrimsTest
OptimizationAlgorithmsTest
AntColonyOptimizationTest
AntTest
RandomSwapTest
SimulatedAnnealingTest
TwoOptTest
Utils
target
crimeSample.csv
info6205.spring2023.teamproject.csv
pom.xml
README.md
External Libraries
Scratches and Consoles
package OptimizationAlgorithmsTest;
import ...
Chaman Betrabet
public class AntColonyOptimizationTest {
2 usages
private double[][] pheromone;
2 usages
private double[][] distance;
5 usages
private AntColonyOptimization aco;
2 usages
private int numAnts;
2 usages
private int numIterations;
2 usages
private double alpha;
2 usages
private double beta;
2 usages
private double evaporation;
2 usages
private double Q;
7 usages
Run:
AntColonyOptimizationTest
Tests passed: 2 of 2 tests – 4 ms
AntColonyOptimizationTest (Optii 4 ms
testSolve 3 ms
testgetNumCities 1 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 2 (moments ago)
19:25
LF
UTF-8
4 spaces
main


INFO6205_Project
src
test
java
OptimizationAlgorithmsTest
AntTest
testChooseNextCity
SimulatedAnnealing.java
HungarianTest.java
OddVerticesTest.java
PrimsTest.java
AntColonyOptimizationTest.java
AntTest.java
package OptimizationAlgorithmsTest;
import ...
Chaman Betrabet
public class AntTest {
Chaman Betrabet
@org.junit.jupiter.api.Test
public void testChooseNextCity()
{
Ant ant = new Ant(startCity: 0, numCities: 5);
double[][] pheromone = {{0, 1, 1, 1, 1}, {1, 0, 1, 1, 1}, {1, 1, 0, 1, 1}, {1, 1, 1, 0, 1}, {1, 1, 1, 1, 0}};
double[][] distance = {{0, 2, 2, 2, 2}, {2, 0, 2, 2, 2}, {2, 2, 0, 2, 2}, {2, 2, 2, 0, 2}, {2, 2, 2, 2, 0}};
double alpha = 1.0;
double beta = 2.0;
ant.chooseNextCity(pheromone, distance, alpha, beta);
int nextcity = ant.getTour().get(1);
assertTrue(condition: nextcity >= 0 && nextcity <= 4);
assertTrue(ant.getVisited()[nextcity]);
}
Run:
AntTest
Tests passed: 4 of 4 tests – 14 ms
AntTest (OptimizationAlgorithms 14 ms
testCalculateProbabilities() 11 ms
testMove() 1 ms
testSelectNextCity() 1 ms
testChooseNextCity() 1 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 4 (a minute ago)
22:1
LF
UTF-8
4 spaces
main


INFO6205_Project
src
test
java
OptimizationAlgorithmsTest
RandomSwapTest
test3
RandomSwapTest.java
tour.add(1);
double graph[][] = {{0, 5, 8, 999},
{5, 0, 10, 15},
{8, 10, 0, 20},
{999, 15, 20, 0}};
RandomSwap randomSwap=new RandomSwap();
tour=randomSwap.RandomSwapOpt(tour,graph, numberSwaps: 100);
Prims prims=new Prims();
List<Edge> mst=prims.PrimsAlgorithms(graph);
double costmst=0.0;
for(int i=0;i<mst.size();i++)
costmst+=mst.get(i).getWeight();
CostTraversal costTraversal=new CostTraversal();
double cost=costTraversal.costTraversal(tour, graph.length, graph, source: 1);
assertEquals(costmst,cost,(costmst*1.20));
}
}
Run:
RandomSwapTest
Tests passed: 3 of 3 tests – 6 ms
RandomSwapTest (OptimizationA 6 ms
test1 5 ms
test2 0 ms
test3 1 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 3 (moments ago)
96:1
LF
UTF-8
4 spaces
main


INFO6205_Project
SimulatedAnnealingTest
test3
PrimsTest.java
AntColonyOptimizationTest.java
AntTest.java
RandomSwapTest.java
TwoOptTest.java
SimulatedAnnealingTest.java
Project
INFO6205_Project [Project]
.idea
src
main
java
test
MSTAlgorithmsTest
EulerianCircuit
HungarianTest
OddVerticesTest
PrimsTest
OptimizationAlgorithmsTest
AntColonyOptimizationTest
AntTest
RandomSwapTest
SimulatedAnnealingTest
TwoOptTest
Utils
target
crimeSample.csv
info6205.spring2023.teamproject.csv
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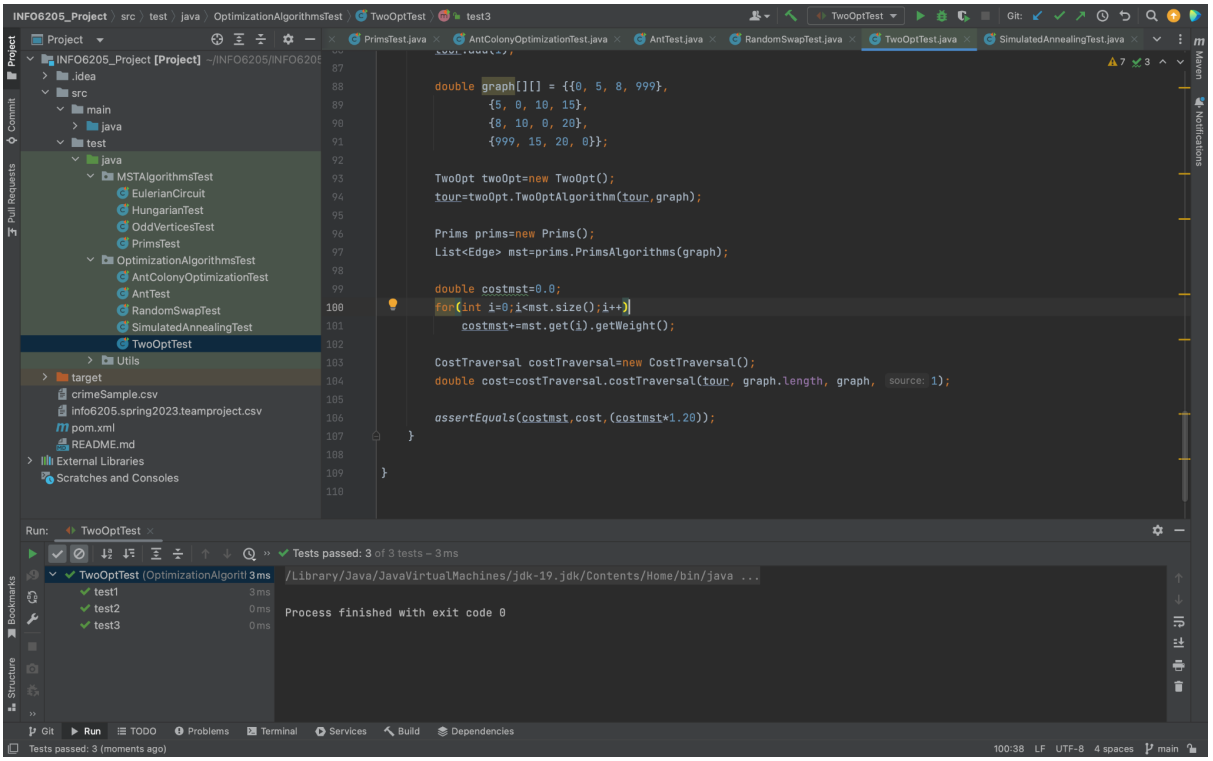
Scratches and Consoles
costmst+=mst.get(i).getWeight();
CostTraversal costTraversal=new CostTraversal();
double cost=costTraversal.costTraversal(tour, graph.length, graph, source: 1);
assertEquals(costmst,cost,(costmst*1.20));
Chandan Anandachari
@Test
public void test3(){
List<Integer> tour=new ArrayList<>();
tour.add(1);
tour.add(0);
tour.add(2);
tour.add(3);
tour.add(1);
double graph[][] = {{0, 5, 8, 999},
{5, 0, 10, 15},
{8, 10, 0, 20},
{999, 15, 20, 0}};
SimulatedAnnealing simulatedAnnealing=new SimulatedAnnealing();
Run:
SimulatedAnnealingTest
Tests passed: 3 of 3 tests – 1 min 24 sec
SimulatedAnnealingTest (C 1 min 24 sec
test1 28 sec 854 ms
test2 25 sec 762 ms
test3 29 sec 558 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 3 (moments ago)
84:21
LF
UTF-8
4 spaces
main


INFO6205_Project
TwoOptTest
test3
PrimsTest.java
AntColonyOptimizationTest.java
AntTest.java
RandomSwapTest.java
TwoOptTest.java
SimulatedAnnealingTest.java
Project
INFO6205_Project [Project]
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src
main
java
test
MSTAlgorithmsTest
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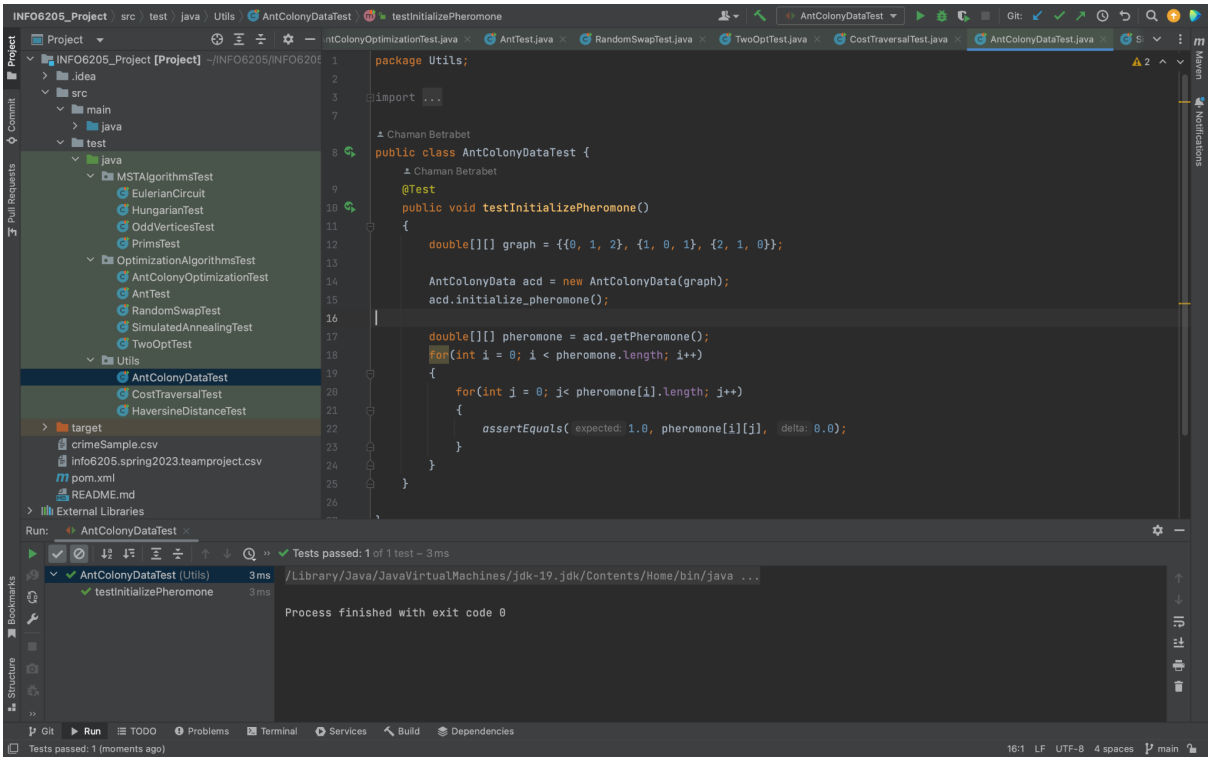
double graph[][] = {{0, 5, 8, 999},
{5, 0, 10, 15},
{8, 10, 0, 20},
{999, 15, 20, 0}};
TwoOpt twoOpt=new TwoOpt();
tour=twoOpt.TwoOptAlgorithm(tour,graph);
Prims prims=new Prims();
List<Edge> mst=prims.PrimsAlgorithms(graph);
double costmst=0.0;
for(int i=0;i<mst.size();i++)
costmst+=mst.get(i).getWeight();
CostTraversal costTraversal=new CostTraversal();
double cost=costTraversal.costTraversal(tour, graph.length, graph, source: 1);
assertEquals(costmst,cost,(costmst*1.20));
Run:
TwoOptTest
Tests passed: 3 of 3 tests – 3 ms
TwoOptTest (OptimizationAlgorit 3 ms
test1 3 ms
test2 0 ms
test3 0 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 3 (moments ago)
100:38
LF
UTF-8
4 spaces
main


INFO6205_Project
src
test
java
Utils
AntColonyDataTest
testInitializePheromone
AntColonyDataTest
Git:
Project
INFO6205_Project [Project]
.idea
src
main
java
test
java
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EulerianCircuit
HungarianTest
OddVerticesTest
PrimsTest
OptimizationAlgorithmsTest
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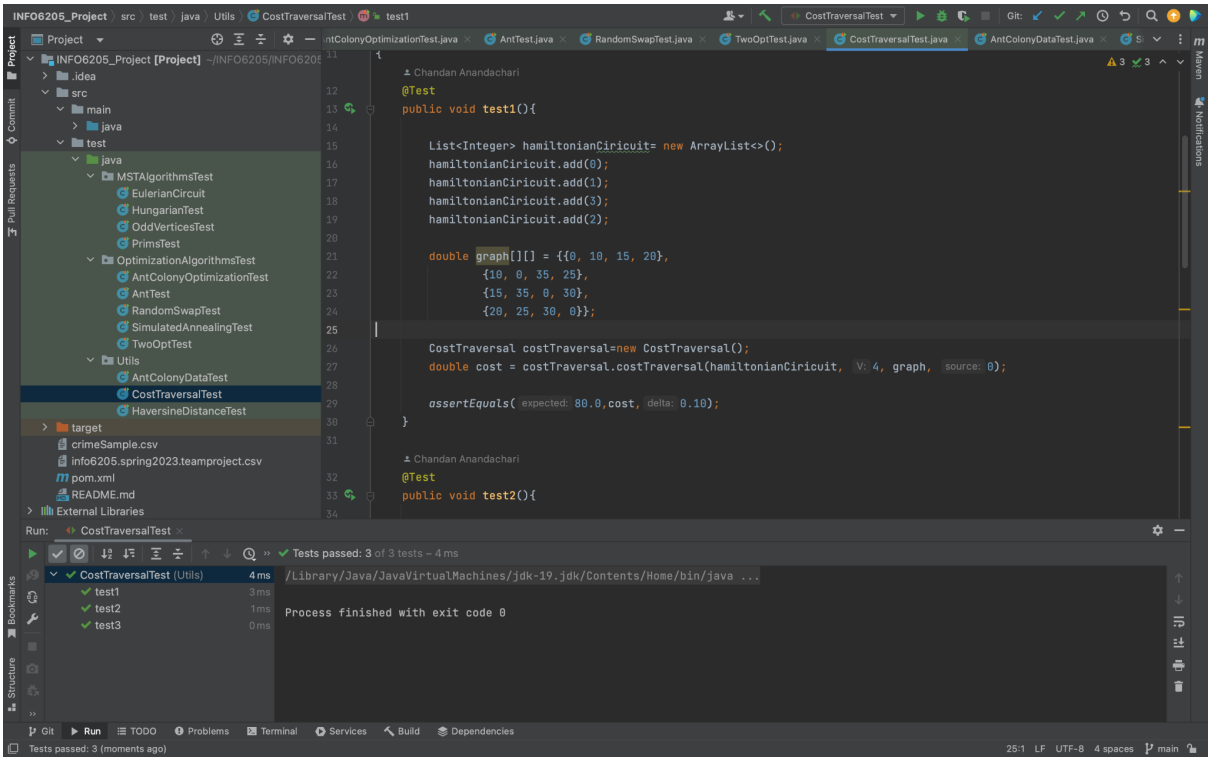
CostTraversalTest.java
AntColonyDataTest.java
package Utils;
import ...
Chaman Betrabet
public class AntColonyDataTest {
Chaman Betrabet
@Test
public void testInitializePheromone()
{
double[][] graph = {{0, 1, 2}, {1, 0, 1}, {2, 1, 0}};
AntColonyData acd = new AntColonyData(graph);
acd.initialize_pheromone();
double[][] pheromone = acd.getPheromone();
for(int i = 0; i < pheromone.length; i++)
{
for(int j = 0; j< pheromone[i].length; j++)
{
assertEquals(expected: 1.0, pheromone[i][j], delta: 0.0);
}
}
}
Run:
AntColonyDataTest
Tests passed: 1 of 1 test – 3 ms
AntColonyDataTest (Utils) 3 ms
testInitializePheromone 3 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 1 (moments ago)
16:1
LF
UTF-8
4 spaces
main


INFO6205_Project
CostTraversalTest
test1
Project
INFO6205_Project [Project]
.idea
src
main
java
test
java
MSTAlgorithmsTest
EulerianCircuit
HungarianTest
OddVerticesTest
PrimsTest
OptimizationAlgorithmsTest
AntColonyOptimizationTest
AntTest
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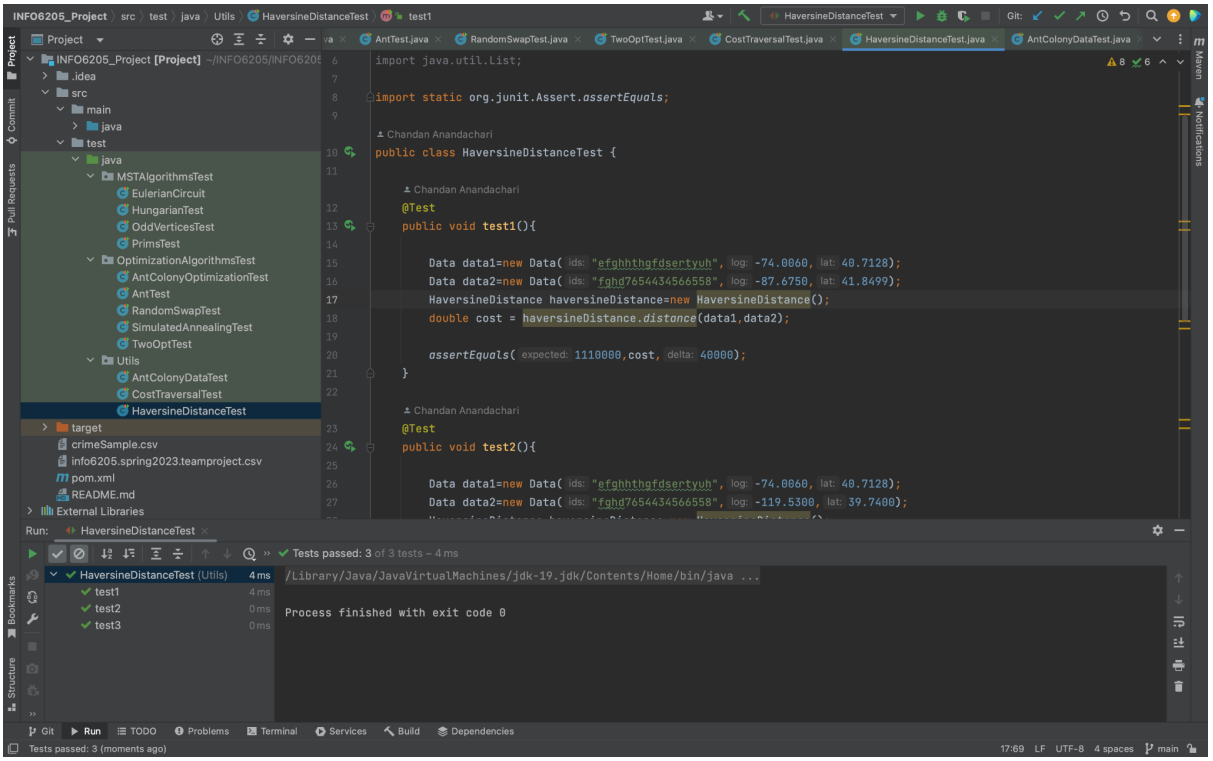
AntTest.java
RandomSwapTest.java
TwoOptTest.java
CostTraversalTest.java
AntColonyDataTest.java
Chandan Anandachari
@Test
public void test1(){
List<Integer> hamiltonianCiricuit= new ArrayList<>();
hamiltonianCiricuit.add(0);
hamiltonianCiricuit.add(1);
hamiltonianCiricuit.add(3);
hamiltonianCiricuit.add(2);
double graph[][] = {{0, 10, 15, 20},
{10, 0, 35, 25},
{15, 35, 0, 30},
{20, 25, 30, 0}};
CostTraversal costTraversal=new CostTraversal();
double cost = costTraversal.costTraversal(hamiltonianCiricuit, V: 4, graph, source: 0);
assertEquals(expected: 80.0,cost, delta: 0.10);
}
Chandan Anandachari
@Test
public void test2(){
Run:
CostTraversalTest
Tests passed: 3 of 3 tests – 4 ms
CostTraversalTest (Utils) 4 ms
test1 3 ms
test2 1 ms
test3 0 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 3 (moments ago)
25:1 LF UTF-8 4 spaces main


INFO6205_Project
HaversineDistanceTest
test1
Project
INFO6205_Project [Project]
.idea
src
main
java
test
java
MSTAlgorithmsTest
EulerianCircuit
HungarianTest
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PrimsTest
OptimizationAlgorithmsTest
AntColonyOptimizationTest
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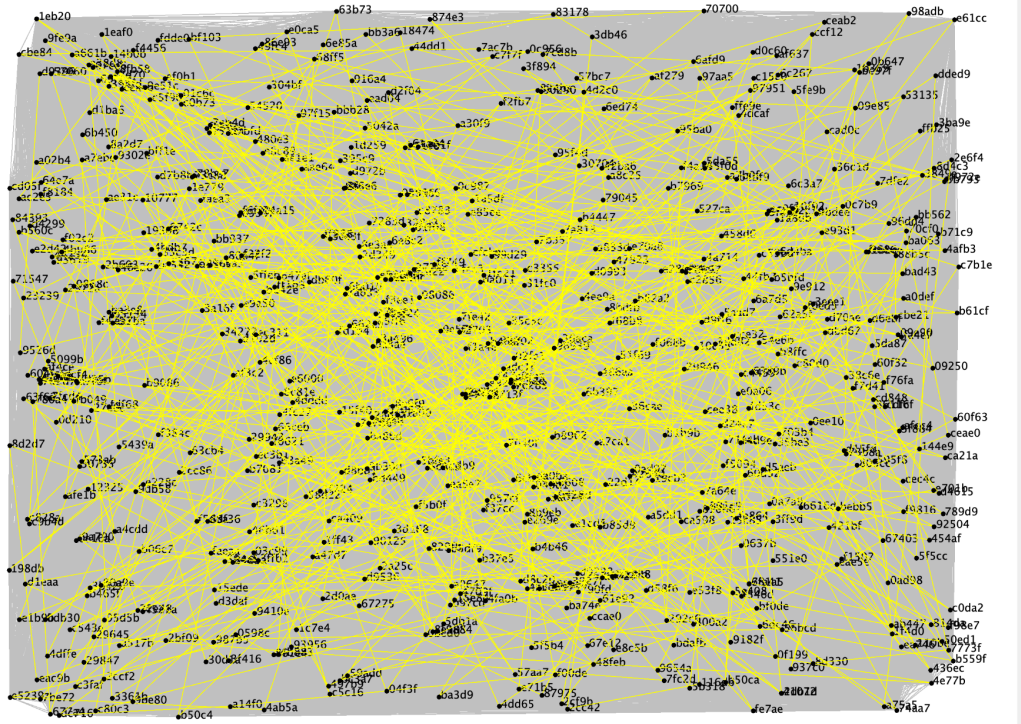
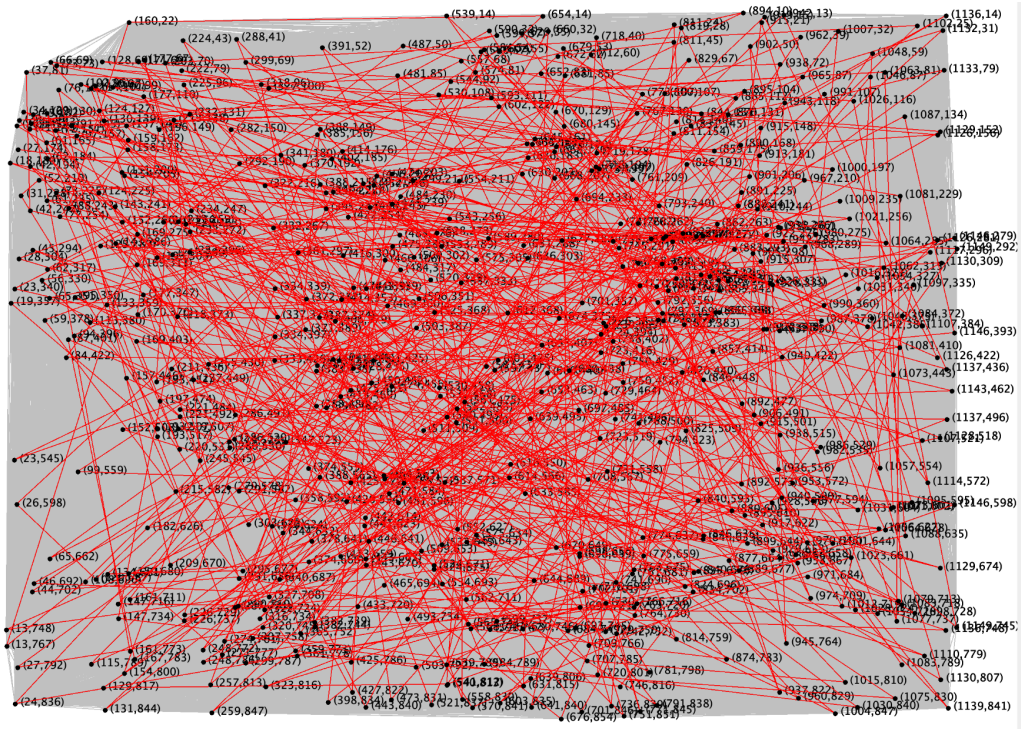
RandomSwapTest.java
TwoOptTest.java
CostTraversalTest.java
HaversineDistanceTest.java
AntColonyDataTest.java
import java.util.List;
import static org.junit.Assert.assertEquals;
Chandan Anandachari
public class HaversineDistanceTest {
Chandan Anandachari
@Test
public void test1(){
Data data1=new Data(ids: "efghhthgfdsertyuh", log: -74.0060, lat: 40.7128);
Data data2=new Data(ids: "fghd7654434566558", log: -87.6750, lat: 41.8499);
HaversineDistance haversineDistance=new HaversineDistance();
double cost = haversineDistance.distance(data1,data2);
assertEquals(expected: 1110000,cost, delta: 40000);
}
Chandan Anandachari
@Test
public void test2(){
Data data1=new Data(ids: "efghhthgfdsertyuh", log: -74.0060, lat: 40.7128);
Data data2=new Data(ids: "fghd7654434566558", log: -119.5300, lat: 39.7400);
Run:
HaversineDistanceTest
Tests passed: 3 of 3 tests – 4 ms
HaversineDistanceTest (Utils) 4 ms
test1 4 ms
test2 0 ms
test3 0 ms
/Library/Java/JavaVirtualMachines/jdk-19.jdk/Contents/Home/bin/java ...
Process finished with exit code 0
Git
Run
TODO
Problems
Terminal
Services
Build
Dependencies
Tests passed: 3 (moments ago)
17:69 LF UTF-8 4 spaces main

OUTPUT



Christofides Algorithm
Random Swapping
2-Opt
Simulated Annealing
Ant Colony
Reset
Cost:
643752.48156754



Christofides Algorithm
Random Swapping
2-Opt
Simulated Annealing
Ant Colony
Reset
Cost:
655148.8545234395

Conclusion:

In this report, we investigated the effectiveness of the Christofides algorithm and its optimization methods, including tactical methods such as random swapping and 2-opt improvement, and strategic methods such as simulated annealing and ant colony optimization, in obtaining high-quality approximate solutions to the traveling salesman problem.

Based on our findings, the Christofides method produced high-quality approximate solutions with a worst-case performance guarantee of 1.5 times the optimal solution. The addition of optimization methods such as random swapping and 2-opt improvement further improved the solution quality. Simulated annealing and ant colony optimization were also effective in improving the solution quality but required careful parameter tuning.

In order to assure the program's accuracy, we used object oriented programming principles and unit tests to develop the Christofides algorithm and its optimization methods in Java. We generated datasets of various sizes to test the performance and accuracy of the program.

We discovered that the 2-opt improvement technique within the simulated annealing optimization method provided significant improvements in the solution quality. This approach was able to escape from the local optima and enhance the solution quality while still allowing for sufficient exploration of the solution space.

In conclusion, our program implementation in Java provides a practical tool for solving the problem, and future research optimization methods and their combination to achieve even better results.

References:

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2. de Oliveira da Costa, P. R., Rhuggenaath, J., Zhang, Y., & Akcay, A. (2021). Learning 2-opt heuristics for the traveling salesman problem via deep reinforcement learning. IEEE Transactions on Neural Networks and Learning Systems, 32(4), 1698-1709. http://proceedings.mlr.press/v129/costa20a/costa20a.pdf
3. MathWorks. (n.d.). Minimization Using Simulated Annealing Algorithm. Retrieved April 16, 2023, from https://www.mathworks.com/help/gads/simulated-annealing-examples.html
4. Rudidev. (2020, November 2). 2-opt explaind | TSP optimization tutorial and visualization [Video]. Retrieved from https://www.youtube.com/watch?v=wsEzZ4F_bS4&ab_channel=Rudidev
5. LearnbyExample. (2021, May 18). Solving the Travelling Salesman Problem using Ant Colony Optimization [Video]. Retrieved from https://www.youtube.com/watch?v=oXb2nC-e_EA&t=472s&ab_channel=LearnbyExample