

ENS 491/492 – Graduation Project

Final Report

Project Title:

Urban Deliveries Using Autonomous Robots

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1. EXECUTIVE SUMMARY

With the increasing popularity of autonomous robots in urban deliveries, supply chain structures of companies, almost every industry has faced a crucial change. From large companies to small businesses almost every service sector started using autonomous robots frequently in the urban delivery process. This project will mainly examine the urban delivery operations using autonomous robots which are focusing on the delivery process of the product to the customer. Furthermore, the project will consider the real-life constraints such as economic, environmental, social, sustainability, and health and safety which are faced by autonomous robots in the urban delivery process to understand and establish a rigid formulation. Moreover, features of different autonomous robots which are used by different companies will be researched detailly to construct healthy mathematical modeling and an efficient solution outcome for the project. Vehicle Routing Problem is a mixed integer linear programming formulation which is used to find optimal routes for multiple vehicles visiting a set of customer locations. Main motivation of this project is to investigate different types of urban deliveries which are using autonomous robots from a routing viewpoint, and deal with the problem as an extension of the Vehicle Routing Problem (VRP). Furthermore, goal of the project is to formulate the problem with based on Vehicle Routing Problem (VRP) methodology and to propose an efficient solution within the Sabancı University map. Applicable programming language will be selected to code the established mathematical modeling with the goal of obtaining an efficient solution for the problem within the Sabancı University map. After these stages, Savings Algorithm will be used as a heuristic, and the problem will be evaluated from the viewpoint of the selected heuristic algorithm with coding the heuristic with an applicable programming language. Consequently, the solution found by the mathematical formulation and the approximate solution obtained by the Savings Algorithm will be compared to examine how two different approaches achieve results and provide a healthy comparison with focusing on the lacking parts and the prominent parts of both approaches.

2. PROBLEM STATEMENT

Our main motivation in this project is to meet the demands of various customer points within the Sabancı University map by using electric vehicles. As a group, our aim in this project is to reach the specific features of the autonomous robots we want to use, to create mathematical formulation and to develop an efficient heuristic algorithm. Moreover, as a group we plan to visualize the routes obtained by the two approaches and compare them by looking at their objective function values. The fact that giant companies such as Amazon and Uber Eats abroad can deliver packages with electric vehicles is an important factor that motivates us in this project. Furthermore, the main motivating factor for us is the presence of companies such as Yemeksepeti and Hepsiburada that deliver packages with autonomous robots in Turkey. Lastly, the most important example that motivated our group in the project was Deliveroo. AI's delivery of packages using autonomous robots at Istanbul Technical University Teknokent. Based on this example that has already been achieved, we tried to reflect this process on the Sabancı University map in line with our planned goals in our graduation project.

2.1. Objectives/Tasks

Project will focus on firstly investigating the companies which are using autonomous robots in their delivery process of the product to the customer. After that, project will concentrate on finding crucial features of the autonomous robots to construct a rigid mathematical formulation. Moreover, appropriate programming language will be selected, and the created mathematical modeling will be coded by approaching the problem as a vehicle routing problem and to create an optimal set of routes for the autonomous robots including all the demand points within the Sabancı University map. Another crucial objective of the project is to develop an efficient heuristic and code the selected heuristic by using an appropriate programming language by considering the constraints that the problem consists of. Last objective of the project is to evaluate the outcomes provided by mathematical formulation and heuristic. The results of the two approaches will be evaluated by comparing the visualized routes and the objective function values with focusing on the lacking parts and the prominent parts of both approaches.

2.2. Realistic Constraints

Economic: There is no budget allocated for the project. The “Last-Mile” of package delivery is one of the most expensive and labor- intensive process in the supply chain management. Moreover, there is a fixed cost for each electric vehicle used and there is a maintenance cost for electric vehicles, for facilities and for the charging stations as well. Lastly, the project will consider the setup cost, maintenance cost and unit delivery cost for each electric vehicle used.

Environmental: There are no environmental constraints for this project due to the enhanced technology that autonomous robots have already used. With the help of electrical energy there will be less air pollution, no emission problems, less greenhouse gases will be released to the atmosphere, and global warming threat will be reduced as well. Moreover, in the future solar energy can become a good option for the autonomous robots to enhance the charge situation.

Social: Due to the aim of this project, package deliveries will be carried out with autonomous robots. Couriers will be replaced by robots. This process needs to be reflected to society in the most efficient and least damaging way.

Health and Safety: Autonomous robots can be stolen. Also, products can be stolen from autonomous robots as well. Moreover, the private information of the workers and the customers should be kept safe in the system against the hackers. Furthermore, due to the enhanced technology of the autonomous robots there will be less noise and pollution which is very beneficial for the health of society.

Sustainability: Autonomous Robots can survive under social, economic, and environmental conditions. Electrical energy is a nature-friendly and sustainable source that can adapt to extreme working conditions if the service is done well and regularly.

Mathematical modeling is a very crucial formulation technique which has a goal of finding the optimal value in which an objective function is maximized or minimized when subjected to various constraints. Moreover, mathematical modeling is useful for guiding quantitative decisions in almost every sector. In our mathematical modeling in the graduation project, we defined the sets, the parameters, the decision variables, the objective function, and the constraints to find the optimal objective function value which has a goal of minimizing the total distance travelled by utilizing minimum number of electric vehicles and it minimizes the fixed cost for the electric vehicles used. Moreover, another crucial goal of our mathematical formulation is to

provide the optimal set of routes for the electric vehicles to meet the demand of the clients within the Sabancı University map.

Mathematical Notation Table:

Sets:

V Set of all customers where $V = \{1, \dots, N\}$

V_0 Set of all customers and the depot where $V_0 = \{0, \dots, N\}$

Parameters:

t_{ij} Travel time from node i to node j

d_{ij} Distance from node i to node j

e_i Earliest start time for node i

l_i Latest start time for node i

s_i Service time at node i

F Cost of each robot

Q Battery capacity of each robot

C Cargo capacity of the vehicle

h_{ij} Energy consumption rate to travers arc (i, j)

q_i Demand of customer i

Decision Variables:

x_{ij} 1 if arc (i, j) is traversed by a vehicle; 0 otherwise

b_i Service start time of node i by one of the vehicles

u_i Load on the vehicle upon its arrival at node i

y_i Represents the battery state of charge on departure from station i

Mathematical Modeling:

$$\min \sum_{i,j \in V_0} d_{ij} x_{ij} + F(\sum_{i \in V_0} x_{0i}) \quad (1)$$

subject to:

$$\sum_{j \in V_0} x_{ij} = 1, \forall i \in V \quad (2)$$

$$\sum_{i \in V_0} x_{ij} = 1, \forall j \in V \quad (3)$$

$$b_i + s_i + t_{ij} - M(1 - x_{ij}) \leq b_j, \quad \forall i \in V_0, \forall j \in V \quad (4)$$

$$e_j \leq b_j \leq l_j, \quad \forall j \in V_0 \quad (5)$$

$$0 \leq u_j \leq u_i - q_i x_{ij} + C(1 - x_{ij}), \quad \forall i \in V_0, \forall j \in V, i \neq j \quad (6)$$

$$0 \leq u_0 \leq C \quad (7)$$

$$q_j \leq u_j \leq C, \quad \forall j \in V_0 \quad (8)$$

$$\sum_{j \in V} x_{0j} \geq 1 \quad (9)$$

$$0 \leq y_j \leq y_i - (h \cdot d_{ij}) x_{ij} + Q(1 - x_{ij}), \quad \forall_i \in V_0, \forall_j \in V, i \neq j \quad (10)$$

$$y_0 = Q \quad (11)$$

$$y_i \geq \sum_{\substack{i \in V_0 \\ i \neq j}} (h \cdot d_{ij}) x_{ij}, \quad i \in V_0 \quad (12)$$

$$x_{ij} \in (0, 1), \quad i, j \in V_0 \quad (13)$$

$$b_i \geq 0, \quad i \in V_0 \quad (14)$$

$$u_i \geq 0, \quad i \in V_0 \quad (15)$$

$$y_i \geq 0, \quad i \in V_0 \quad (16)$$

Descriptions:

- (1): The objective function minimizes the total distance travelled by utilizing minimum number of EVs and minimizes the fixed cost for the vehicles used. F is a sufficiently large constant that represents a fixed cost for the vehicles.
- (2), (3): These constraints are the flow balance constraints which ensure that each customer is visited exactly once.
- (4): This constraint keeps track of time at customers and the depot.
- (5): This constraint ensures the service time window restrictions.
- (6), (7): These constraints guarantee that demand of all customers is satisfied.
- (8): This constraint provides the link between customer demand and the cargo capacity. It ensures that the load on the vehicle is not less than the customer demand and not greater than the cargo capacity of the vehicle.
- (9): This constraint ensures that the number of vehicles leaving the depot is greater than 1.
- (10), (11): These constraints keep track of the battery state of charge and make sure that it is never negative.
- (12): This constraint guarantees that the vehicle never runs out of battery.
- (13), (14), (15), (16): These constraints are used to show our decision variables and their ranges.

After obtaining an outcome from the mathematical model, as a group we focused on developing a heuristic algorithm to find an approximate solution as we planned during the project process. We decided that the Savings Algorithm would be a useful heuristic for the problem, and it will give us an efficient solution within the Sabancı University map. Moreover, due to the structure of our problem we updated the Savings Algorithm by including the time window and battery capacity restrictions. The Savings Algorithm described detailly in the methodology part. Lastly, as planned in the project process the solution found by the mathematical formulation and the approximate solution obtained by the Savings Algorithm will be compared to examine how two different approaches achieve results and to provide a healthy comparison with focusing on the lacking parts and the prominent parts of both approaches.

3. METHODOLOGY

Savings Heuristic:

Savings Algorithm is a widely known heuristic which is used for solving large traveling salesman problems (TSP) and vehicle routing problems (VRP). Distances between the demand nodes are very crucial to establish a solid solution because Savings Algorithm is a heuristic which is based on the customer distances. Moreover, customer demands, and vehicle capacity are very significant points for the algorithm to provide efficient solution for the problems in terms of its structure. If the problem is a traveling salesman problem (TSP), each customer should be visited exactly once, and their demands will be met. Moreover, only one tour will be constructed, since the vehicle capacity is sufficient for all customers one vehicle will handle the tour. If the problem is a vehicle routing problem (VRP), similarly each customer should be visited exactly once, and more than one vehicle will be used due to the vehicle capacity constraint; therefore, multiple routes will be established. Savings method considers these constraints, which are the feasibility conditions of traveling salesman problems and vehicle routing problems. Due to the structure of our problem, we added time window and battery capacity restrictions to the Savings Heuristic. We evaluate vehicle capacity, battery capacity and time window of the clients in our revised Savings Algorithm. Savings Method starts with selecting an any city as the “depot” and calls it as city “0”. Then, conceptually form routes from the depot to each customer. After that, algorithm calculates all the savings for joining two customers with the following formula $S_{ij} = C_{io} + C_{oj} - C_{ij}$, where S_{ij} represents the savings for node i and j , and C_{ij} represents the distances between node i and j . Furthermore, method orders the savings from largest to smallest and starts forming routes by linking customer nodes with each other according to its savings values. While doing that, method doesn't break any links which are formed earlier and stops when all customers are on the route and turn back to the depot. Savings Heuristic considers vehicle capacity, battery capacity and time window of the customers when forming the routes. If the current vehicle capacity and battery capacity of the tour cannot add the new customer to the tour and there is a time window mismatch, the tour is terminated and a new tour is created, and the algorithm continues. Moreover, if the distance matrix in the problem is symmetric then there will be $(n-1) \cdot (n-2) / 2$ savings to calculate. On the other hand, if the distance matrix in the problem is asymmetric there will be $(n-1) \cdot (n-2)$ savings to calculate. Consequently, if we evaluate the Savings Method generally, we can see that we can add new customer nodes either to the

beginning or to the end of the existing route which is a crucial inference for us while implementing the structure of the code. Furthermore, general summary of the Savings Method is provided visually in the below. Lastly, to further improve the result, we obtained with Savings Heuristic and to make a healthier comparison with the optimal solution we found with the mathematical formulation, we added 2-opt, the local search method, to our Savings Heuristic python code. 2-opt is a modification algorithm for traveling salesman problems and vehicle routing problems. Algorithm takes 2 arcs from the existing route, reconnects these arcs with each other and calculates the new traveling distance. If this modification has led to a shorter total travel distance the current route is updated. Thanks to the 2-opt algorithm, we improved the result obtained from the Savings Algorithm, we achieved a better visualization of the established tours within the Sabancı University map and were able to make a healthier comparison of both approaches.

4. RESULTS & DISCUSSION

As we aimed at the beginning of the project, we researched companies which are using autonomous robots in their delivery process of the product to the customer. As a group, we reduced our research to two main examples and investigated the specific features of the autonomous robots used by these two companies. Lastly, we preferred to pursue with the Starships Robot, and we used the features of the Starships Robot in our graduation project.

Robot Features Table:

Name	<i>Delivers.AI</i>	<i>Starships Robot</i>
Travel Speed	8 km/h	6 km/h
Range	1.5 km diameter area	2.4 diameter area
Carrying Capacity	20 kg (44 lbs)	10 kg (22 lbs)
Volume	90 Liters	22 Liters
Tires	4-Tires. It can climb 20cm sidewalks curbs.	6-Tires. Boogie system for climbing curbs
Setup Cost	4000 Euros	2250 Dollars
Maintenance Cost	500 Euros	500 Dollars
Delivery Cost per unit	4 Euros	1.99 Dollars
Battery Capacity	1220 Wh – 1280 Wh	1260 Wh 12h + driving time
Charging Time	3 hours	45 minutes

After finalizing the significant features of the Starships Robot, we calculated the robot energy consumption rate per km which is very crucial for the project by using some of the features in the above table. Robot energy consumption rate per km was calculated as $1260 \text{ (robot battery capacity)} / 2.4 \text{ (it is the range of the robot, the diameter area which means that it can travel at most 2.4 km with fully charged)} = 525$. Lastly, these calculated and found features were used in mathematical formulation and in the python code as parameters.

The project was conducted in line with the initial objectives. Thanks to an efficient research process, companies using autonomous robots in package delivery were researched, and various information, sample videos and academic articles were obtained. Then, the specific features of the selected autonomous robot were investigated, mathematical modeling was created and coded with the python programming language. Moreover, an efficient heuristic was developed, and the selected heuristic was coded with the python programming language as well. Furthermore, the routes obtained within Sabancı University were visualized and the two approaches were compared with each other according to their objective function values. Lastly, the project covers all the initial objectives and has reached a successful conclusion. In this section of the Final Report the results obtained will be presented to the reader in detail. The results will be carefully analyzed and compared with each other.

Output and Visualization of Mathematical Modeling:

```
EVRPTW.setParam('MIPFocus', 3)
EVRPTW.setParam('MIPGapAbs', 100)
EVRPTW.setParam('TimeLimit', 7200)
```

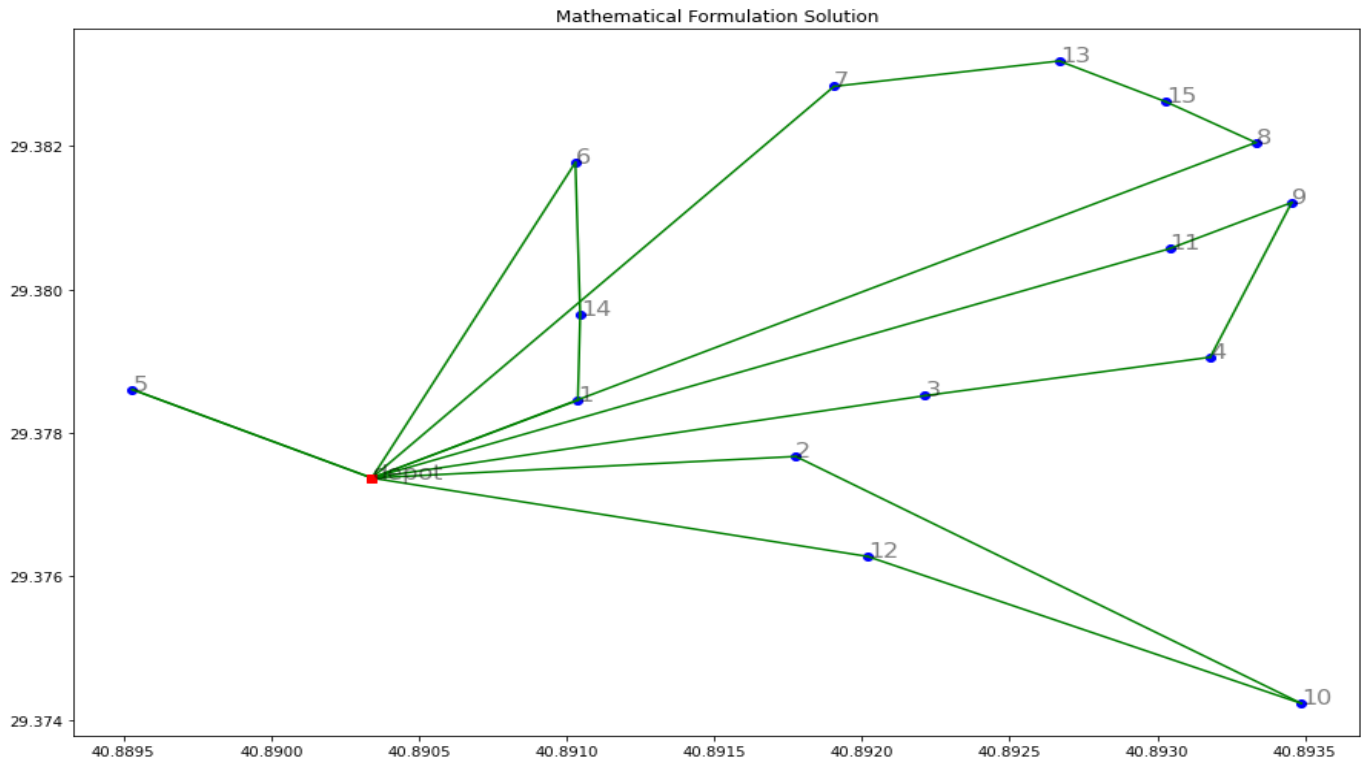
```
Time limit reached
Best objective 1.376422505966e+04, best bound 2.754973162434e+03, gap 79.9845%

Model status is: 9

Objective Function value is: 13764.225059663693
```

```
[(0, 1), (0, 5), (0, 7), (0, 11), (0, 12), (1, 14), (2, 0), (3, 0), (4, 3), (5, 0), (6, 0), (7, 13), (8, 0),  
(9, 4), (10, 2), (11, 9), (12, 10), (13, 15), (14, 6), (15, 8)]
```

Since there is an optimality gap problem in our code, we maintained such an approach that focuses on choosing the best feasible solution among the existing solutions in a specified time limit. We run the code for two hours and we choose the best feasible solution as our main solution among the formed solutions within two hours. Moreover, due to this approach optimality gap was reduced to 80%. As shown in the above screenshot the objective function value of our mathematical modeling code is 13764.225059663693. The objective function focuses on minimizing the total distance traveled by using minimum number of electric vehicles and it minimizes the fixed cost for each vehicle used. According to the result of mathematical formulation, we obtained a solution which is based on 5 different tours. Limitations such as time window and service time restrictions of customers, cargo and battery capacity of electric vehicles are evaluated, and with a total of 5 different tours, the demands of the customers on the Sabancı University map are met by visiting each customer exactly once. Moreover, the tours within the Sabancı University map are visualized in the screenshot below. First tour starts with the depot, which goes to customers 1, 14 and 6 respectively. After finishing the tour electric vehicle turns back to depot. Second tour starts with the depot, goes to customer 5 and turns back to the depot. Third tour starts with the depot, which goes to customers 7, 13, 15 and 8 respectively. After finishing the tour autonomous robot turns back to depot. Fourth tour starts with the depot, goes to customers 11, 9, 4 and 3 respectively. After finishing the tour electric vehicle turns back to depot as usual. The last tour starts with depot and goes to customer 12, after visiting customer 12 the electric vehicle goes to customer 10 and after meeting the demands of customer 10 it goes to customer 2 and turns back to the depot. Lastly, the detailed version of the output table is provided in the Appendix section as well.



Output and Visualization of Savings Heuristic:

VRP solution found with savings heuristic starting from 0 is:

[0, 13, 15, 8, 0]

[0, 9, 11, 0]

[0, 7, 6, 0]

[0, 3, 4, 0]

[0, 2, 12, 10, 0]

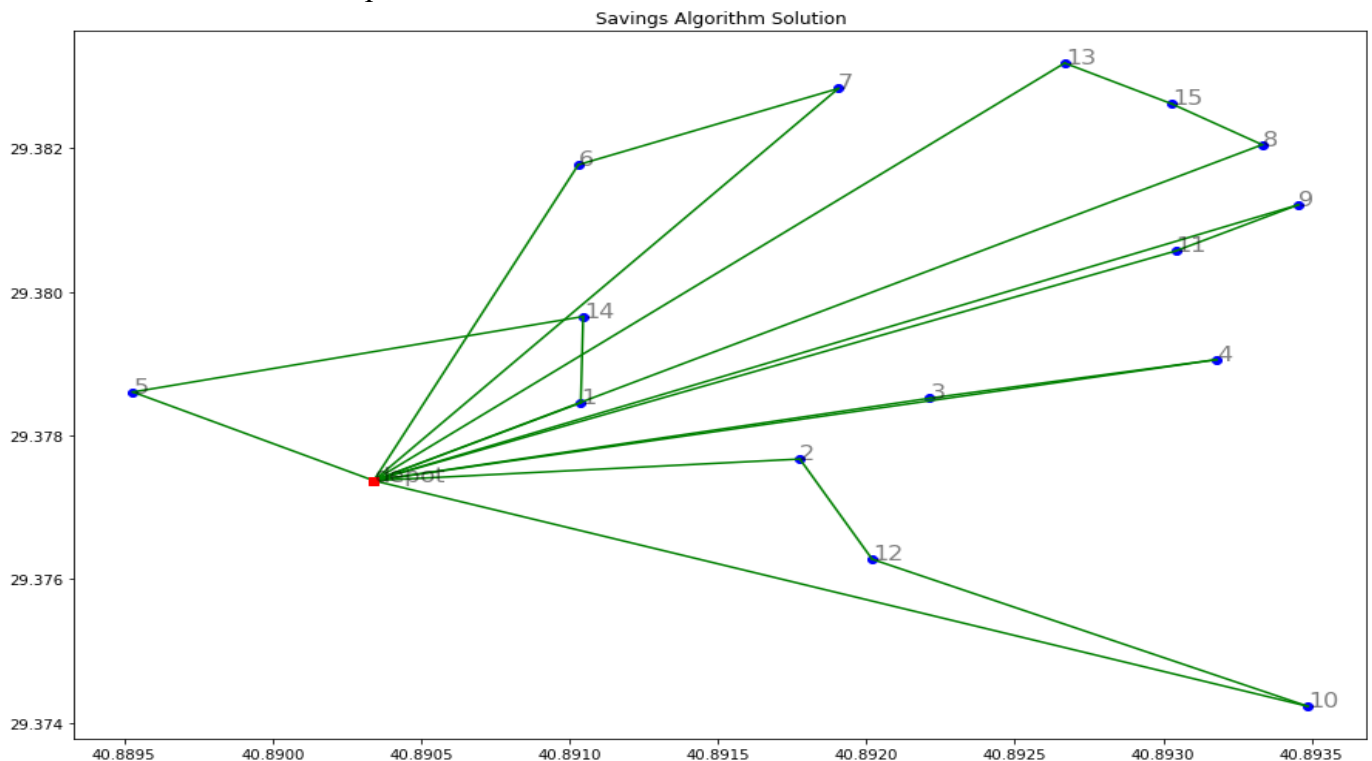
[0, 1, 14, 5, 0]

With a Total Traveling Distance of: 5.34

Including the Total Traveling Distance and the Total Cost for Used Electric Vehicles: 16517.34

The solution found by using Savings Heuristic has an objective function value of 16517.34 as shown in the screenshot above. The objective function focuses on minimizing the total distance traveled by using electric vehicles and it minimizes the fixed cost for each vehicle used. According to the result of Savings Heuristic, we obtained a solution which is based on 6 different

tours; therefore, solution of Savings Heuristic has a high objective function value, because more electric vehicles are used to create routes. Limitations such as time window restrictions of customers, cargo and battery capacity of electric vehicles are evaluated, and Savings Heuristic was updated based on these limitations. Moreover, with a total of 6 different tours, the demands of the clients on the Sabancı University map are met by visiting each customer exactly once. Furthermore, the tours within the Sabancı University map are visualized in the screenshot below. First tour starts with the depot, which goes customers 13, 15 and 8 respectively. After finishing the tour electric vehicle turns back to depot. Second tour starts with the depot, which goes to customers 9 and 11 respectively. After finishing the tour electric vehicle turns back to depot as well. Moreover, third tour starts with the depot as usual and visits customer 7 first, after visiting customer 7 tour continues with customer 6 and turns back to the depot after visiting customer 6. Fourth tour starts with the depot, goes to customers 3 and 4 respectively. After finishing the tour electric vehicle turns back to depot. Furthermore, tour 5 starts with the depot, goes to customers 2, 12 and 10 respectively. After finishing the tour electric vehicle turns back to depot as usual. The last tour starts with depot and goes to customer 1, after visiting customer 1 the electric vehicle goes to customer 14 and after meeting the demands of customer 14 it goes to customer 5 and turns back to the depot.



Comparison and Discussion:

The two objective function values obtained from two different approaches are close to each other. It shows that these two approaches reveal logical results, and both the mathematical modeling result and the Savings Heuristic result confirm each other. We met the demands of customers within the Sabancı University map with the result we obtained with the mathematical modeling, using 5 vehicles in total, with 5 different tours. On the other hand, we used 6 vehicles in total with the Savings Heuristic and visited customers with 6 different tours. When we consider these, there is a slight increase in the distance covered in Savings Heuristic solution, since one extra vehicle is used, the price also increases as well. All this causes the objective function to increase somewhat compared to the objective function value of the mathematical modeling solution. Lastly, when we look at the Visualization Tables, the routes obtained with the two different approaches generally agree with each other which is a crucial indicator of both solutions maintained a logical approach according to the characteristics of the data set.

Big Data Results:

Instance Name	Your algorithm Solution without 2-Opt		Your algorithm Solution with 2-Opt		GAP %
	# V	OFV	# V	OFV	
c101_21	83	506103,62	83	506103,62	0,00%
c109_21	48	292684,75	48	292684,75	0,00%
c201_21	61	400951,99	61	400951,99	0,00%
c208_21	42	319313,88	42	319313,88	0,00%
r101_21	99	500296,2	99	500296,2	0,00%
r112_21	19	138464,23	19	138464,23	0,00%
r201_21	67	386139,12	67	386139,12	0,00%
r211_21	38	242227,46	38	242227,46	0,00%
rc101_21	96	647812,98	96	647812,98	0,00%
rc108_21	33	281984,66	33	281984,66	0,00%
Average	58,6	371597,889	58,6	371597,889	0
# V	Number of vehicles used in your solution				
OFV	Objective Function Value				

We tested the 10 large instances data provided to us on our Savings Heuristic Algorithm code. In these datasets there are 100 customers, and the required robot features are given such as vehicle battery capacity, vehicle load capacity and energy consumption rate. Moreover, we adjusted the provided datasets according to convenient format of our problem. Due to the structure of our problem, we ignored the recharging situation; therefore, we extracted recharging station, inverse refueling rate, and average velocity information from the dataset provided to us. We tested the data on our python code after adjusting it. Furthermore, the two solutions for each instance one with our Heuristic Algorithm without 2-Opt and another one with 2-Opt was reported and compared with each other in order to provide improvements. Lastly, as seen in the figure above, we transferred the obtained results to the excel file named "Results" provided to us.

5. IMPACT

The results we obtained because of this project have very important scientific, socio-economic, and technological effects. The project went through a long period of research. Various articles were reviewed, examples, resources and specifications for autonomous robots were found. Moreover, the project was based on the vehicle routing problems (VRP) methodology, which is a completely scientific subject, and mathematical formulation has been formed. After that, the project was also evaluated from a heuristic viewpoint and solution found by the mathematical formulation and the approximate solution obtained by the heuristic was compared to examine how two different approaches achieve results and lacking parts and the prominent parts of both approaches were highlighted. The coding processes made using the Python programming language strengthened the scientific effects of the project as well. Furthermore, the project has significant socio-economic impacts. The main idea of the project is to use autonomous robots instead of couriers in last mile package deliveries. The replacement of couriers by autonomous robots is not an instant process, but thanks to such projects, society's adaptation to this change is accelerating. In addition, the project has significant economic impacts as well. Due to this project the couriers' salary will be saved and this money will be used for autonomous robots. Furthermore, this project will also have significant environmental impacts. Since autonomous robots are using electrical energy; therefore, there will be less air pollution, no emission problems, less greenhouse gases will be released to the atmosphere, and

global warming threat will be reduced as well. Lastly, the technological impact of the project is an undeniable achievement. The main element of the project is autonomous robots, which is advanced technology. Thanks to this project, delivery with autonomous robots, which was previously realized only in Istanbul Technical University within the university and only performed by various companies in the country, is also modeled on the map of Sabancı University. If this project is realized through an initiative, it will be a significant academic example project for other universities and will also prepare an important infrastructure for the increase in the popularity of autonomous robots throughout Turkey.

6. ETHICAL ISSUES

- Research process must underline the preferences that were covered.
- The information and the articles collected during the research process should be kept.
- Permission may be needed for related data information and current examples.
- The dataset provided by the supervisor for the project should be kept.
- The results obtained in the Sabancı University map should be kept throughout the project process.

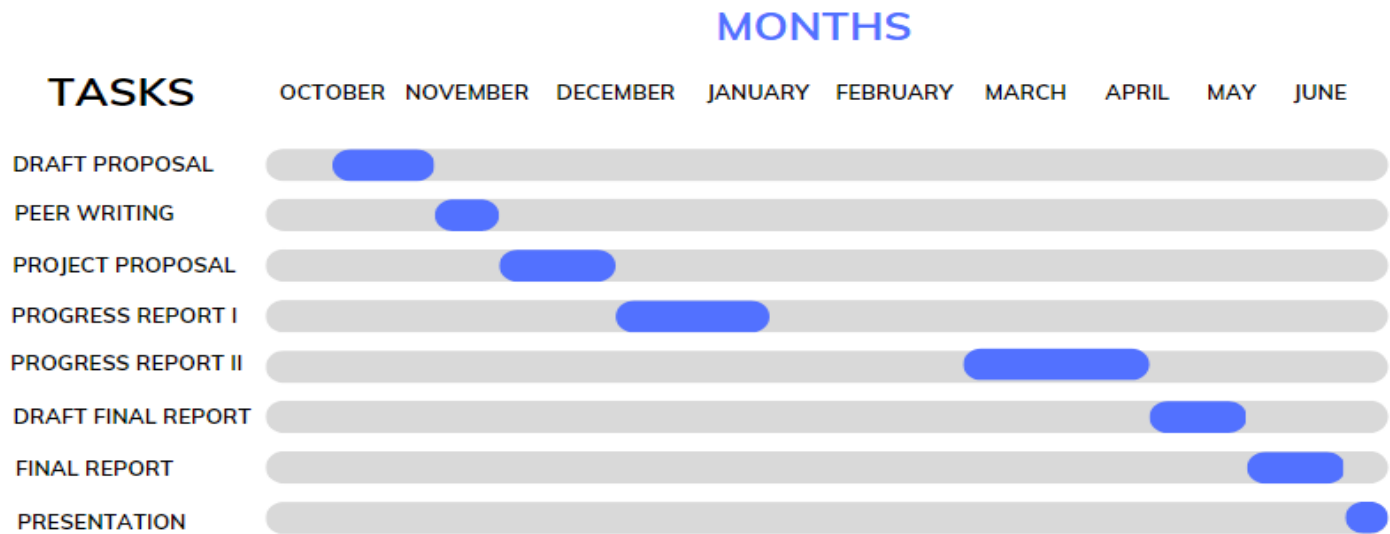
7. PROJECT MANAGEMENT

Initially, we got a lot of information about the project, thanks to the different resources our supervisor gave us and to our various internet resources. While conducting our project, we preferred to assign a task leader for each task, but to progress by sharing the work equally with everyone in each task. Due to this approach, we aimed for everyone to have knowledge in every task and targeted to use the time in the most efficient way.

Every step in the project is very critical, so any delay in any planned task means that the entire process that we have decided on will be disrupted. To keep project delays minimum, each group member should complete their tasks on time by paying attention to their responsibilities. If someone is unable to complete his task on time, he should ask for assistance from the other group members to avoid any delays in the progress of the project.

In the ENS 491 course, which is the first stage of the project process, we researched companies which are using autonomous robots in the urban delivery process. Moreover, as a group we preferred our autonomous robot that we are going to use in our project, and we researched the specific features that the autonomous robot consists of which are very crucial for us to establish a rigid mathematical formulation. Furthermore, in the second stage of our project which is ENS 492 course we constructed a mathematical model considering the needs that the problem consists of, and we coded the established mathematical formulation by using the python as a programming language and we solved the problem using the gurobi as an optimization tool. After that, as a group we selected the Savings Algorithm as a heuristic and coded the selected heuristic by using python as a programming language to reach an approximate solution. Lastly, we compared the visualized tours within the Sabancı University map which are reached by two approaches, and we provided a healthy comparison with focusing on the objective function values to display the lacking parts and the prominent parts of both approaches.

During the implementation process, our project plan has encountered minor changes. Due dates of some tasks shifted due to the change in the academic calendar of the Sabancı University. Moreover, as a group, we could not complete the specific work required for some tasks when we planned, due to our busy schedule on some dates, but we worked simultaneously and kept the delays minimum. Thanks to this graduation project, as a group we learned a lot of crucial information about project management. Working as a team, controlling the process correctly and time management are just some of the important gains we have added to ourselves in this project. Lastly, as a team we hope that we will use this project management information we have gained thanks to this project both in our future academic projects and in the projects we will encounter in business life as well.



8. CONCLUSION AND FUTURE WORK

The companies that use autonomous robots in package deliveries were examined and the specific features of the selected autonomous robots were investigated. Another important result of the project was the infrastructure of the first-time use of autonomous robots on the Sabancı University map optimally has been established. Mathematical modeling has been done, Heuristic Algorithm has been developed and these algorithms have been tested thanks to the dataset provided to us. Moreover, these routes created within the Sabancı University map were visualized and the two approaches were compared with each other to display the lacking parts and the prominent parts of both approaches. The next logical step of the project is to prefer one of the solutions methodologies of the problem and focus on it to compensate for its lacking parts. If mathematical modeling is to be progressed, the model should be reviewed, various additions should be made according to the conditions of the problem, and the optimality gap problem should be solved, and an optimal solution should be obtained. On the other hand, if Savings Heuristic is to be progressed, the model should be reviewed and rather than 2-opt algorithm more advanced local search methods such as k-exchange algorithm should be implemented to obtain an efficient approximate solution. Furthermore, if an investment can come, we, as the project group, can make the necessary adjustments with our project supervisor and can be implemented this autonomous robot delivery system in real life within the Sabancı University map, just like did in the Istanbul Technical University.

9. APPENDIX

Output Table of Mathematical Modeling:

```
Time limit reached
Best objective 1.376422505966e+04, best bound 2.754971992416e+03, gap 79.9845%

Model status is: 9

Objective Function value is: 13764.225059663693
x0,1 1.000000
x0,5 1.000000
x0,7 1.000000
x0,11 1.000000
x0,12 1.000000
x1,14 1.000000
x2,0 1.000000
x3,0 1.000000
x4,3 1.000000
x5,0 1.000000
x6,0 1.000000
x7,13 1.000000
x8,0 1.000000
x9,4 1.000000
x10,2 1.000000
x11,9 1.000000
x12,10 1.000000
x13,15 1.000000
x14,6 1.000000
x15,8 1.000000
b1 150.000000
b2 180.005737
b3 210.000000
b4 194.980598
b5 210.000000
b6 270.000000
b7 15.081823
b8 180.020161
b9 90.000000
b10 135.000000
b11 74.988163
b12 119.960447
b13 134.936964
b14 195.049398
b15 165.010427
```

```
u0 10.000000
u1 9.000000
u2 3.000000
u3 3.000000
u4 6.000000
u5 3.000000
u6 4.000000
u7 10.000000
u8 3.000000
u9 7.000000
u10 8.000000
u11 10.000000
u12 10.000000
u13 7.000000
u14 8.000000
u15 5.000000
y0 1260.000000
y1 1197.192251
y2 844.271326
y3 120.535512
y4 181.650272
y5 72.156005
y6 1050.881646
y7 381.120267
y8 270.443468
y9 286.178301
y10 1026.149925
y11 323.462982
y12 1150.738870
y13 333.950469
y14 1144.161163
y15 301.103023
[(0, 1), (0, 5), (0, 7), (0, 11), (0, 12), (1, 14), (2, 0), (3, 0), (4, 3), (5, 0), (6, 0), (7, 13), (8, 0),
(9, 4), (10, 2), (11, 9), (12, 10), (13, 15), (14, 6), (15, 8)]
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