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Integer Linear Programming Approach for the Personnel Shuttles Routing Problem in Yildiz Campus in Istanbul

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ABSTRACT

The Vehicle Routing Problem (VRP) revolves around the challenge of determining optimal vehicle routes for a company to efficiently serve a specific number of customers while minimizing costs. The Personnel Shuttle Routing Problem (PSRP) is a specialized variation of the VRP which focuses on optimizing shuttle or transportation services for individuals or small groups in specific contexts like universities, institutions or corporate campuses. The PSRP is of interest mostly in developed countries as it can lead to improved transportation efficiency, reduced environmental impact, and enhanced passenger satisfaction. This article details an optimization study conducted to address the PSRP within Yildiz Technical University's Yildiz campus in 2021. The primary objective is to identify routes that minimize travel distances while ensuring balanced service coverage, all while adhering to specific constraints. The optimization approach leverages Integer Linear Programming to formulate a mathematical decision model. Data and information pertinent to the problem were acquired through consultations with the Yildiz Technical University General Secretary Support Unit managers. The resulting decision model was implemented using the GAMS 34.3.0 software package as a decision analytic programme, and the problem was solved by splitting it into two parts, addressing the Anatolian and European sides of the campus separately. The study culminated in a notable achievement: a reduction of 10.88% in the travel distances associated with Yildiz campus personnel shuttle routes.

1. Introduction

The Vehicle Routing Problem (VRP) consists of designing the lowest cost delivery routes through a geographically dispersed set of customers, subject to a several constraints. This issue is central to distribution management and is faced by tens of thousands of carriers worldwide every day. The problem arises in various ways due to diverse constraints encountered in practice. For over 60 years, VRP has captured the attention of the operational research community [1].

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VRP was officially introduced to the literature for the first time in 1959 by Dantzig and Ramser [2] as the "Truck Dispatching Problem". The authors presented a simple paired heuristic for VRP and presented the mathematical model. They talked about the method they put forward in their article as a generalized version of the traveling salesman problem. They presented their methods with an application on vehicles that will deliver gasoline to gas stations. To define VRP; is an optimization problem that involves determining the best routes or improving existing routes in line with different parameters and purposes so that one or more vehicles can carry products, people, or services to one or more customers with one or more warehouses. The most common purposes for VRP can be compiled as follows [3]:

i. Minimization of the distance traveled by the vehicles or indirectly the transportation costs of the vehicles,
ii. Minimization of the number of vehicles operating on the routes to be created to achieve the objectives,
iii. Balancing the travel times of routes and therefore vehicles between each other,
iv. Balancing the workload and occupancy rates of routes and thus vehicles among each other,
v. Minimization of additional costs and inefficiencies that may occur due to discrete distributions during customer demand satisfaction.

In 1964, Clarke and Wright [4] developed the method introduced by Dantzig and Ramser and presented one of the most famous heuristics to the literature. The development and applications of exact solution methods for VRP date back to the 1980s. Two papers published by Christofides et al. [5], [6] dealt with dynamic programming and q-routes and k-degree centripetal tree methods with minimum span. In 1984, Laporte et al. [7] introduced the first cutting plane method, customized for VRP, which has supported the basis for future studies. This time, Laporte and Nobert [8] published a study in which they compiled exact solution methods algorithms for VRP in the literature in 1987. In 1995, Laporte and Osman [9] compiled nearly 500 articles and publications on four basic routing problems. These four basic problems are Traveling Salesman Problem, Vehicle Routing Problem, Chinese Postman Problem, and Rural Postman Problem. Bowerman et al. [10] published a study in 1995 on the multi-purpose optimization of school shuttle buses with clustering as the first step and routing as the second step. In Dethloff’s article on vehicle routing and reverse logistics in 2001, the researcher used a new sub-tour elimination constraint that sorts the nodes within the route on the use of vehicle routing in his mathematical model [11].

Li and Fu [12] presented multi-objective mathematical models on School Bus Routing Problem (SBRP) and suggested constraints in 2002. Their models offer many possible optimizations. Bektaş and Elmastaş [13] developed a model suitable for integer programming of an SBRP and made an application in 2004. In their model, they added a cost variable depending on the number of vehicles to the objective function. Schittekat et al. [14] presented a mathematical model for SBRP that forms the basis of the literature in 2006. This model includes three more detailed decision variables including whether the vehicles go to the stops, whether they stop at the stops and whether they pick up passengers from the stops. Bektaş and Elmastaş [15] presented an integer linear programming model for the routing of school buses in 2007. Düzakın and Demircioğlu [16] wrote a publication on VRP and solution methods, and also brought an important categorization study to the literature in 2009. Uzumer and Eren [17] carried out an application with a decision variable that can calculate vehicle occupancy and sequencing in a model they developed for the SBRP in 2012. Yuan et al. [18] wrote a detailed review and article on using Miller-Tucker-Zemlin's sub-round elimination constraints on time windowed vehicle routing problems in 2020.

The excessive use of energy and the resulting pollution pose a great ecological and environmental threat. Therefore, many researchers participate in green campaigns to protect the environment by minimizing the damage [19]. In the VRP domain, an emerging area called the green vehicle routing problem (GVRP) has become attractive by many researchers [20]. The majority of work in GVRP focuses on optimizing the energy consumption of transportation [21]. More environmentally friendly practices have been sought, especially in the past decade, due to the increasing knowledge about the dangerous effects of transport activities, which have a significant impact on the ecological environment [22]. By evaluating different aspects of using alternative fuels in VRP, the effects of different pollutants on human health and the ecosystem have been examined through various mathematical models [23]. In 2011, Bektaş and Laporte introduced Pollution Routing Problem (PRP), which aims to determine a VRP that creates less pollution by providing lower CO_2 emissions [24]. Recently, the discrete PRP of Bektaş and Laporte has been extended to a continuous case by Xiao et al. [25]. Lekburapa et al. (2021) present an improvement on Bektaş et al. (2004)'s sub-round elimination constraint by establishing an approach to maximize passenger satisfaction based on passenger and stop distance for School Bus Routing Problem (SBRP) [26].

In the following sections, the personnel shuttle service routing problem to be implemented will be defined, the data will be presented, the integer decision model used for the solution will be introduced and the solution results will be shared and explained.

2. Methodology

2.1 Problem Definition

In the application performed within the scope of this study, the vehicle routing of the shuttles serving for the university personnel at Yildiz campus of Yildiz Technical University (YTU) in Istanbul is examined. In this integer optimization programming case study, it is aimed to minimize the total travel distance.

Table 1
All available services in the problem

Service No	Service name	Sides	Capacity	Number of people using the service
1	Yıldız-Halkalı Lodging	Europe	17	9
2	Yıldız-Gültepe-Ayazağa-Bahçeköy	Europe	17	8
3	Yıldız-Beykoz	Anatolia	17	8
4	Yıldız-Dudullu-Çekmeköy-Yenidoğan	Anatolia	27	22
5	Yıldız-Sultanbeyli-Kurtköy-Uğurmumcu	Anatolia	17	8
6	Yıldız-Fındıklı	Anatolia	17	6
7	Yıldız-Kadıköy-Kartal	Anatolia	17	13
8	Yıldız-Beşyüzevler-Yeşilpınar	Europe	17	8
9*	Yıldız-Tuzla-Şifa Mh.-Kartal	Anatolia	27	22
10	Yıldız-Haznedar-Davutpaşa Lodging	Europe	27	23

The services currently used are demonstrated in Table 1 (the table listing all available service routes). In the solution phase, the problem is divided into two main parts. These are the European and Anatolian side routes. The stops on both sides are optimized internally. The reason for this is the assumption that in any optimal outcome there will not be a service serving both the European and Anatolian sides. The main reason for this is that there are no stops for a vehicle leaving the university to stop before entering the bridge road. Another important reason is that a vehicle that will operate on both sides has a very long and costly route. Thus, the problem becomes less complex, the solution time is shortened, and the workload to be endured while creating the distance matrix decreases by approximately 75%.

Another assumption is that the Yıldız-Şifa Mahallesi line, service number 9* in Table 1, is excluded from the optimization problem. The reason for this is that this line serves from start to finish on the D100 (E5; highway road) highway. The service, which uses this road from the bridge, never leaves the main road and stops at many stops on the main road. Since exiting and re-entering D100 in any case would be very costly and cause a waste of time, it was decided to keep service line 9 as it is and to carry out an optimization study on the remaining stops. Thus, the optimization study is carried out for a total of 42 stops and 105 passengers on both sides.

Currently, there are 105 personnel using the shuttle service at Yildiz campus of YTU, which is included in the optimization problem. One route has been removed from the problem because of the inability to change its stops. In this direction, there are a total of 42 stops in the Anatolian and European sides, where 105 personnel are dropped off. Eighteen (18) of these stops are on the European side and twenty four (24) stops are on the Anatolian side. Currently, there are nine (9) personnel shuttles used for the Yildiz campus. Four (4) of these nine (9) services operate on the European side and the rest of them (five) operate on the Anatolian side. The service company provides services to the university personnel in two different capacities as 17 and 27 people. In the solution phase, the problem is divided into two parts; The European and Anatolian routes.

Table 2
European side stops and passenger numbers

No	Stops	Passenger Numbers
1	Fulya Sitesi (Lojman, Halkalı)	5
2	Halkalı Çınaryolu	2
3	Sefaköy Armoni Park	2
4	Çeliktepe Meydan	3
5	Sanayii Mh. Meydan	2
6	Ayazağa Oyak Sitesi	1
7	Bahçeköy Merkez (Sarıyer)	2
8	Nurtepe	1
9	Alibeyköy	1
10	Yeşilpınar	1
11	Gazi Mh.	1
12	Küçükköy Merkez	1
13	Beşyüzevler	1
14	Topçular (Haliç)	2
15	Davutpaşa Lojman	14
16	Soğanlı Meydan	5
17	Bağcılar Yunusemre Köprüsü	2
18	Yüzyıl Köprüsü (Esenler)	2
	Total	**48**

Table 2 shows the European side stops and the number of passengers getting off at each stop. There are a total of 18 different stops and 48 passengers (academic and administrative staff) on this side. Stop names are given randomly as numeric values from one to maximum stop number, without any order in terms of proximity to the starting point as Yildiz Campus.

Table 3
Anatolian side stops and passenger numbers

No	Stops	Passenger Numbers
1	Ferah Mh. (Ümraniye)	1
2	Kazım Karabekir Mh.	1
3	Kanlıca	1
4	Beykoz Merkez	2
5	Ortaçeşme	3
6	Şelaleyolu Tepeüstü	5
7	Çamlık	8
8	Sarıgazi	4
9	Taşdelen	3
10	Paşaköy Sapağı (Çekmeköy çıkışı)	2
11	Uğurmumcu	3
12	Soğanlık Orta Mh.	2
13	Kurtköy Merkez	2
14	Sultanbeyli Gölet	1
15	Mustafa Kemal Mh.Örnek Sitesi	1
16	Novada AVM	1
17	Fındıklı Mh. Muhtarlık Önü	2
18	Tatlısu	2
19	Evlendirme Dairesi	2
20	Göztepe Marmara Uni.	4
21	Bostancı Merkez	3
22	İdealtepe	2
23	Maltepe Merkez	1
24	Kartal Merkez	1
	Total	**57**

Table 3 shows the Anatolian side stops and the number of passengers getting off at each stop. There are a total of 24 different stops and 57 passengers (academic and administrative staff) on this side.

The shuttles do not return to the campus when their route ends, they continue other stops directed by the company based on the contract which the university has stipulated. For each side, a maximum capacity and number of vehicles currently used on that side can be allocated. It is not desirable for the vehicles to stay on the route longer than the vehicle with the longest travel time (different for both sides) within the existing routes. The current service routes of the problem can be seen in Tables 4 and 5.

Table 4
European side existing shuttle routes

Num.	Shuttle 1	Shuttle 2	Shuttle 3	Shuttle 4
Capacity	17	17	17	27
Routes & Stops	0	0	0	0
	1	4	8	15
	2	5	9	16
	3	6	10	17
		7	11	18
			12	
			13	
			14	

Table 4 demonstrates the capacities, routes and stops of the existing services, based on the stop numbers specified in Table 2. Stop number zero (0) is the starting point of the services and represents YTU Yildiz Campus. Currently, four (4) services are actively operating on the European side.

Table 5
Anatolian side existing shuttle routes

Num.	Shuttle 1	Shuttle 2	Shuttle 3	Shuttle 4	Shuttle 5
Capacity	17	27	17	17	17
Routes & Stops	0	0	0	0	0
	1	6	11	15	19
	2	7	12	16	20
	3	8	13	17	21
	4	9	14	18	22
	5	10			23
					24

Table 5 presents the capacities, routes and stops of the existing services, based on the stop numbers specified in Table 3. Currently, five (5) services are actively operating on the Anatolian side.

2.1 Mathematical Model

In this section, an Integer Linear Programming (LP) Model is established to optimize the problem. The parameters, indices, variables, objective function, and constraints of the model are given below. The solution aims to minimize the total distance traveled by the vehicles [11], [14], [27]. The parameters used in the model are presented;

Parameters:

N : Number of stops

M : Number of vehicles

c_{ij} : Travel distance from stop i to stop j (km)

q_k : Capacity of vehicle k

y_j : Number of passengers at stop j

t : Average travel time per kilometer (min/km)

T : Maximum route time for vehicles (min)

“0” : Starting point-Campus

“1, …, N” : Stops

“N+1” : Virtual route termination node

Indices:

i, j, p : {0, 1, …, N, N+1}

k : {1, …, M}

Variables:

$$x_{ijk} = \begin{cases} 1, if\ vehicle\ k\ travels\ from\ stop\ i\ to\ stop\ j \\ 0, otherwise \end{cases}$$

a_j = The variable used to prevent sub-tours can also be thought of as the position of the nodes in the route.

Objective Function:

$$minZ = \sum_{i=0}^{N+1} \sum_{j=0}^{N+1} c_{ij} \sum_{k=1}^{M} x_{ijk} \quad (1)$$

Constraints:

$$x_{ijk} = 0, \quad i = j, \ \ k = 1, \dots, M \quad (2)$$

$$\sum_{j=1}^{N+1} x_{0jk} = 1, \quad k = 1, \dots, M \quad (3)$$

$$\sum_{i=1}^{N+1} x_{i0k} = 0, \quad k = 1, \dots, M \quad (4)$$

$$\sum_{i=0}^{N} x_{i(N+1)k} = 1, \quad k = 1, \dots, M \quad (5)$$

$$\sum_{j=0}^{N} x_{(N+1)jk} = 0, \quad k = 1, \dots, M \quad (6)$$

$$\sum_{i=0}^{N} \sum_{k=1}^{M} x_{ijk} = 1, \quad j = 1, \dots, N \quad (7)$$

$$\sum_{i=0}^{N+1} x_{ipk} - \sum_{j=0}^{N+1} x_{pjk} = 0, \quad \begin{matrix} k = 1, \dots, M \\ p = 1, \dots, N \end{matrix} \quad (8)$$

$$a_j \geq a_i + 1 - N\left(1 - \sum_{k=1}^{M} x_{ijk}\right), \quad \begin{matrix} i = 0, \dots, N+1 \\ j = 0, \dots, N+1 \end{matrix} \quad (9)$$

$$\sum_{i=0}^{N+1} \sum_{j=0}^{N+1} x_{ijk} y_j \leq q_k, \quad k = 1, \dots, M \quad (10)$$

$$\left(\sum_{i=0}^{N+1} \sum_{j=0}^{N+1} x_{ijk} c_{ij}\right) t \leq T, \quad k = 1, \dots, M \quad (11)$$

$$x_{ijk} \in \{0,1\} \quad (12)$$

$$a_j \geq 0, \quad \mathrm{j} = 1, \dots, \mathrm{N} \quad (13)$$

Equation (1) is the objective function that aims to minimize the total distance traveled by vehicles. Equation (2) is the constraint that prevents assigning a station to itself and ensures that the variable takes the value 0 in cases where i=j. Equation (3) states that each vehicle exits once from node 0, that is, university campus; Equation (4) is the constraint, which ensures that no vehicle returns to node 0, that is, university campus. Equation (5) states that each vehicle finishes its routes at the virtual route termination node, where there is no cost of going from any stop; Equation (6) is the constraint, which ensures that no exit is made from this node. Equation (7) is the constraint that satisfies the condition of visiting all stops once. Equation (8) is the constraint to establish a connection between the input and output of a node, according to this constraint the number of inputs and outputs to a node is equal. Equation (9) is the constraint that prevents the formation of sub-routes, it lists the nodes in the routes formed, so sub-routes that form a closed loop in themselves are prevented. Virtual variable can be seen as a position of the route, values of the variable works for sorting vehicle stops. Equation (10) is the constraint, which ensures that no vehicle exceeds its capacity. Equation (11) is the constraint that ensures that the maximum route time determined for vehicles is not exceeded, this constraint is used for line balancing in routes with the requests of YTU service managers. Equation (12) is the constraint that allows the decision variable x_{ijk} to be binary. Equation (13) operates as an extension of equation 9. This constraint (13) ensures that the value is positive.

3. Results and Discussion

The problem is solved separately for the European and the Anatolian side, using the mathematical model given in the previous section, in the GAMS 34.3.0 package program, on a computer with INTEL Corei7-9750HF 2.60 GHz processor, 16 GB RAM, Windows 10 Home 64-bit operating system. In the GAMS 34.3.0 package program, it takes 47.172 seconds to find the optimal result for the European side, and 138.953 seconds to find the optimal result for the Anatolian side.

Table 6
European side solution results after optimization

Num.	Shuttle 1	Shuttle 2	Shuttle 3	Shuttle 4
Capacity	17	17	17	27
Routes & Stops	0	0	0	0
	4	8	16	14
	5	9	3	15
	6	10	2	17
	7	12	1	18
		13		
		11		

Table 6 demonstrates the capacities, routes and stops of the services in the optimization solution, based on the stop numbers specified in Table 2. In the optimization solution, a total of four (4) services are actively serving on the European side.

When the optimization results are examined, there is no change in the number of services specific to the European side. Among the existing routes, there is no change in the Çeliktepe-Ayazağa-Bahçeköy route and its stops. But other routes have changed. The differences between the existing European routes and the routes after optimization can be seen on the maps in Figures 1 and 2.

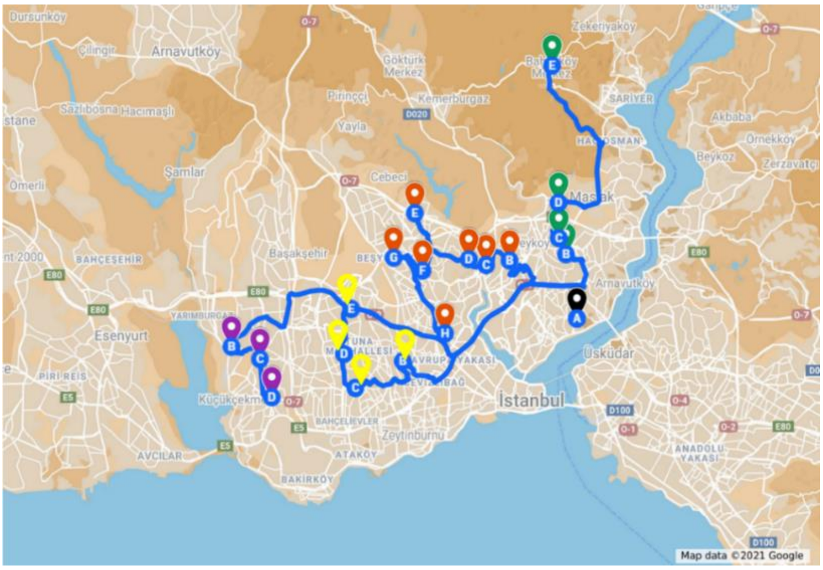

Fig. 1. Existing European routes map

Green, orange, yellow and purple colors in the chart currently represent different service routes on the European side. In total, 4 different routes and 18 different stops are shown in the Figure 1.

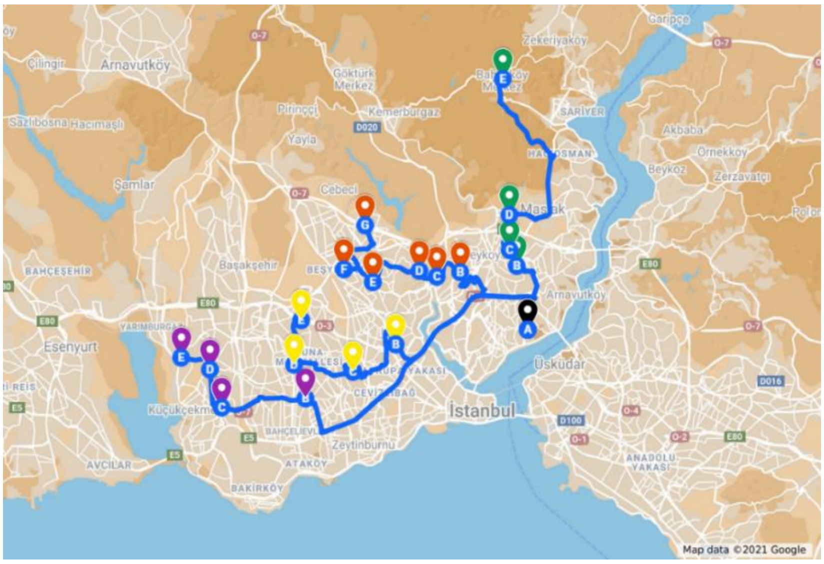

Fig. 2. European routes after optimization map

Green, orange, yellow and purple colors in the chart represent optimized service routes on the European side. In total, 4 different routes and 18 different stops are shown in the Figure 2.

When the optimization results are examined, it has been seen that an additional service is used on the Anatolian side. Among the current routes, there has been no change in the Çamlıca-Kanlıca-Beykoz-Ortaçeşme route and its stops. But all other routes have changed comprehensively.

Table 7
Anatolian side solution results after optimization

Num.	Shuttle 1	Shuttle 2	Shuttle 3	Shuttle 4	Shuttle 5
Capacity	17	27	17	17	17
Routes & Stops	0	0	0	0	-
	1	19	6	15	
	2	20	8	17	
	3	21	10	16	
	4	22	14	18	
	5	23	13	7	
		24		9	
		12			
		11			

Table 7 presents the capacities, routes and stops of the services in the optimization solution, based on the stop numbers specified in Table 3. In the optimization solution, a total of four (4) services are actively serving on the Anatolian side, leaving one service idle (Shuttle 5).

The differences between the existing Anatolian routes and the routes after optimization can be seen on the maps in Figures 3 and 4.

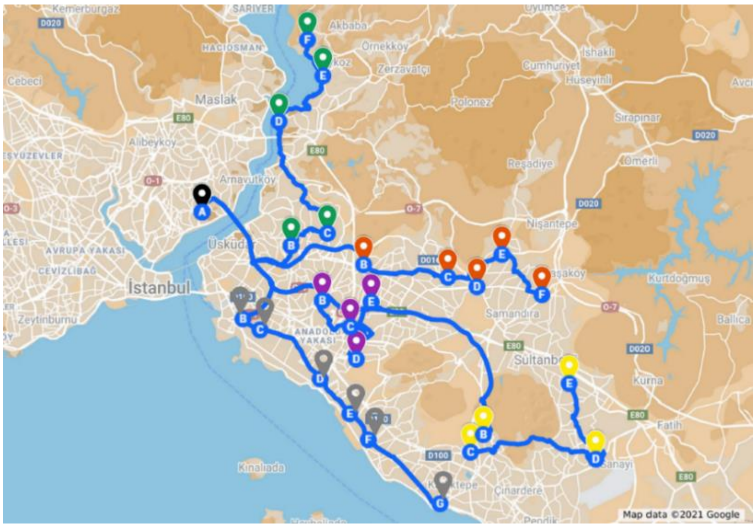

Fig. 3. Existing Anatolian routes map display

The colors Green, Orange, Purple, Gray and Yellow currently represent different service routes on the Anatolian side. A total of 5 different routes and 24 different stops are shown in the Figure 3.

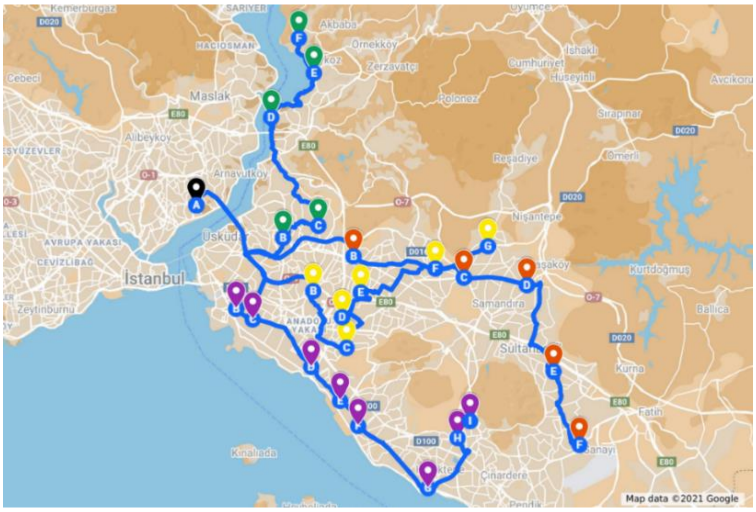

Fig. 4. Anatolian routes after optimization map display

Green, orange, yellow and purple colors represent different service routes on the Anatolian side in the optimization solution. In total, 4 different routes and 24 different stops are shown in the Figure 4.

It can be seen that after the optimization, the Uğurmumcu-Kurtköy vehicle (*Service no 5* in Table 1) is cancelled and the vehicle's passengers are added to different routes. Different routes are also listed to be optimized within themselves. The optimal result is four (4) vehicles for the Anatolian side because one more vehicle leaving the campus and making distribution on the Anatolian side can cause high travel costs.

Table 8
Comparison of optimization results and current situations

Results	European Side	Anatolian Side	Total
Current Situation (km)	114,6	163,1	277,7
Optimization Result (km)	102	145,5	247,5
Improvement (km)	12,6	17,6	30,2
Improvement (%)	10,99%	10,79%	10,88%

When the results are evaluated, a total improvement of 12,6 km is achieved on the European side, which corresponds to a decrease of 10.99%. On the Anatolian side, a total improvement of 17,6 km was achieved and this corresponds to a decrease of 10.79%. When the optimization results are examined based on the distances, it is seen that the routes created to all stops on the Yıldız campus have decreased from the current situation of 277,7 km to 247,5 km per day. In general, a total improvement of 30,2 km has been achieved and this improvement corresponds to a decrease of approximately 10.88%.

Table 9
Daily, monthly and annual earnings on a kilometer basis

Earnings	European Side	Anatolian Site	Total
Daily Earning (km)	12,6	17,6	30,2
Monthly Earning (km)	252	352	604
Annual Earning (km)	3024	4224	7248

It can be seen in Table 9, an improvement in a daily route of 30,2 km corresponds to a gain of 634,2 km per month (21 working days on average) and 7610,4 km per year (252 working days in total). Since there is no system or data where the cost calculation can be made clearly, the net profit rate created by the earnings cannot be calculated. However, based on the estimation of the service managers, with the assumption that an average of 2-2.5 TL per kilometer is paid, there is a cost reduction of roughly 15,000-19,000 TL per year during March 2021, without even taking into account the decrease in the number of services.

It was stated by the YTU Support Services Directorate-Personnel Services officials that the costs per km were in the range of 2-2.5TL in the March 2021 period. In the current situation, discussions were held on the same issue with the officials responsible for YTU Personnel Services in September 2023. For small service vehicles (10-17 people), the average cost is 6 TL/km, and for other large vehicles with 27 people, the average cost is 9 TL per kilometer for September 2023. In summary, the average fuel cost (diesel) for vehicles is stated as 6-9 TL/km. These fuel consumption costs may vary depending on the vehicle's features, engine technology, traffic density on the roads, travel time, vehicle capacity, fuel prices and the length of the route. Accordingly, it is possible to conduct new studies with more detailed and comparative analyses for personnel shuttle routing problems by using a decision analytic software.

4. Conclusion

In this study, as an application, the routing and optimization of Yıldız Technical University Yıldız campus personnel shuttle vehicles are made. In practice, the data are provided by the YTU General Secretary Support Unit and an integer mathematical model is created to solve the problem in the GAMS 34.3.0 package program. In the GAMS 34.3.0 package program, CPLEX optimization solver (IBM ILOG high performance LP/MIP solver) that is provided for the Mixed Integer Programming (MIP) method, is used in a way that is suitable for an integer solution.

The problem is solved by dividing the cluster of stops into two parts, the European and the Anatolian side. For the European side, a 10.99% improvement is achieved, with a total of 12,6 km reduction on the routes. For the Anatolian side, a 10.79% improvement is achieved, with a total of 17,6 km reduction on the routes. To sum up, the total travel distance, which is 277,7 km currently, can be reduced to 247,5 km after optimization per day, and an improvement of 10,88% can be achieved as 30,2 km. These results correspond to an improvement in travel distance of 30,2 km per day, 634,2 km per month (average 21 days), and 7610,4 km per year (252 days in total).

Reducing the number of vehicle routes or total distances in the study also supports an environmental policy for the city. Since there will be less carbon emission to the environment, the proposed solution provides benefits to sustainable city life based on different aspects. It is observed that from 2021 to 2023, driver wages, fuel, automotive components and service costs have increased significantly in Turkey. In this study, it is seen that fuel costs of commercial or service vehicles have increased at least 3 times (300%) based on the years compared as 2021 and 2023. Taken as an example, the costs per km in personnel shuttle transportation at YTU have increased from 2 TL to at least 6 TL. In this case, it becomes clear how important the savings and improvements are in terms of the environment and economy.

For future studies, it has been noticed and recommended that more efficient solutions can be made by establishing integrated mathematical models with dynamic traffic data in cities such as Istanbul where traffic affects daily life a lot. In addition, it seems possible to ease the traffic in the city by making other analyses for the services for the personnel working in public institutions and organizations with the support of public institutions, local governments, and municipalities. At the same time, more accurate balancing will be possible by creating and using time matrices together with distance matrices for time-based line balancing constraints.

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Conflicts of Interest
The authors declare no conflicts of interest.

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