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A study of vehicle routing problems with load-balancing

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Abstract *In a modern business environment, employees are a key resource to a company. Hence, the competitiveness of a company depends largely on its ability to treat employees fairly. Fairness can be attained by using the load-balancing methodology. Develops an integer programming model for vehicle routing problems. There are two objectives, first, to minimize the total distance, and second, to balance the workload among employees as much as possible. We also develop a heuristic algorithm to solve the problems. The findings show that the proposed heuristic algorithm performs well to our 11 test cases.*

Introduction

Most reports on vehicle routing problems focus on decreasing the transportation time and increasing cost efficiency; that is, to search for the best routing, scheduling or loading which will meet customer demand and give the organization the maximum profit. In other words, an organization might pursue to minimize costs at the expense of the load-balance of its employees. When variances among employees' loads are minimized, the costs of the organization usually increase (or the travel path is increased). In Taiwan, when a driver of a transportation company receives his/her daily distribution schedule, he/she needs to finish all the distribution assignments in the same day. The problem is that the assignment may not be fair for each driver. For example, different road or traffic conditions may affect the time to finish the assignment significantly. Currently, most of the assignment schedules of transportation companies in Taiwan are created manually. Every day, the schedulers plan and decide assignment schedules for each driver based on their past experience. Personal preference, insufficient information or other human factors may affect their decision. Eventually, the drivers will compare their assignments with one another and discover discrepancies. Complaints arise, consequently lowering the quality of service. Nowadays, workers (or drivers) are considered a means of competition for a transportation company. It has become more important to cater for the welfare of the employees. Because of this, in planning vehicle routing, transportation companies are pursuing an all-win (organization-employee-customer) strategy by adding the employee work load-balancing factor. This motivates us to do this research. In short, this research tries to build a mathematical model which searches for the shortest travel path and balances drivers' load simultaneously. We also develop a heuristic algorithm to solve the problems.

Definition and categories of vehicle routing problems

The vehicle routing problem is: under some resource (e.g. vehicles or time . . . etc.) restrictions (e.g. load capacity of vehicle, working time), each vehicle has to start from a base to serve every assigned node or arc of a service network and return to the same base meeting the predetermined goal (e.g. minimum cost or shortest distance). Because servicing points can be represented as a node or as an arc of a network, vehicle routing problems can be classified as follows:

- *Node covering problem.* The objective of this type of problem is to serve all the assigned nodes of a network and to meet the stated goal of optimization.
- *Arc covering problem.* The objective of this type of problem is to travel through all the assigned arcs in a network and to meet the stated goal of optimization. Sul and Chang (1993) divides arc covering problems into three parts: arc partitioning problems, arc augmenting problems and arc sequencing problems. In fact, arc covering problems can be solved by considering more than one part of a problem at a time. However, as more parts of a problem are added, the complexity and difficulty of problem solving increases.

This paper studies node covering problems. Bodin *et al.* (1983) have classified vehicle routing problems into seven categories:

(1) Single traveling salesman problems.

(2) Multi-travel salesmen problems.

(3) Single service station with multi-vehicles routing problems.

(4) Multi-service stations with multi-vehicles routing problems.

(5) Single service station with random demand multi-vehicles routing problems.

(6) Chinese postman problems.

(7) Chinese postman problem with load constraints.

This paper focuses on single service station with multi-vehicles routing problems. Besides the aforementioned seven categories, in practice, other variations of vehicle routing problems emerge because of differences in problem characteristics and goals. Chyu and Chen (1996) designed a heuristic algorithm to solve material handling/vehicle routing problems among manufacturing workstations. Lin (1995) considered distribution priority in solving large vehicle problems. Chen and Kuo (1994) developed a two-layer facility location mathematical model to determine locations of distribution centers for delivering food. Viswanathan and Mathur (1997) considered stock warehousing and vehicle routing problems when designing a logistic system. Lee *et al.* (1998) and Lee and Ueng (1998) applied SPT(shortest path theory) in vehicle routing problems. Furthermore Lee (1997) used the integer programming model to determine optimal vehicle size and the best distribution allocation for a hog transportation company. Lee and Ueng (1997) also studied vehicle routing problems in the Farmer's Association Supermarket door-to-door distribution system by determining optimal routes to reach the minimum distribution costs.

All of the above are studies of vehicle routing problems, and each of them only takes one objective into account. None of them has taken employees' welfare into consideration. Chen (1992) applied multi-objective conditions in solving vehicle routing problems. However, the objectives were expressed as vehicle management cost, waiting time cost and delay cost. The multi-objective research in the literature considered labor as an expense and their goal was to minimize labor cost. The welfare of the employees was not discussed. The focus was from the owner's viewpoint, not from the workers'. But, in this paper, the focus is on the workers, or more precisely, the drivers. Since employees are a main ingredient to a successful business, this paper adds in the employee load-balance factor. If workers feel they have been treated fairly in their job assignment, the competitiveness of the company will improve. The all-win strategy (organization-employee-customer) may work. Lee and Tseng (1998) studied a multi-objective vehicle routing problem by bringing in driver load-balancing factors and getting optimal vehicle routing. In that paper, no heuristic algorithm was employed, so the practicality of problem solving is restricted by the size of the problem. In this paper, our goal is to develop an algorithm addressing the load-balancing issue.

Formulation of the integer planning model

This section explains how to conduct an integer planning model which searches the shortest travel path and balances drivers' load simultaneously. First, the problem and research hypothesis are described. Second, the development of a vehicle routing integer programming model under the proposed hypothesis is shown. Third, the characteristics of the model are explained.

Problem explanation and research hypothesis

Under the premise of single service station with multi-vehicles, we study vehicle routing problems with two objectives: the shortest travel path and the best load-balance between employees. What we want to determine is the number of vehicles needed and the paths for each delivery. The size of the vehicle is not discussed in this paper; however, vehicle records for each delivery provide valuable information for adjustment of vehicle size. Our assumptions are as follows:

- *Path and time relation.* Linear relationship between vehicle travel time and distance.
- *Objectives.* Pursuing the shortest travel path and the best load assignment between drivers.
- *Demand for each demand point (node) is known.* Each demand point must be served by only one vehicle. Each node represents a customer.
- *Time.* All of the demand points must be served within a time constraint.

- *Loading/unloading*. At each demand point, only unloading is done.
- *Vehicle travel time*. Within the time constraint, each vehicle makes only one round trip.

Integer programming model

According to the hypothesis, the formulation of the integer programming model is as follows:

$$
\begin{aligned}
\text{Min } Z = {} & \lambda_1 \left(T_a \sum_{i\in 2} \sum_{j\in N} \sum_{k\in N} t_{jk} x_{ijk} \right) + \lambda I \Bigg\{ \Bigg(\Bigg(T_a \sum_{j\in N} \sum_{k\in N} t_{jk} x_{1jk} \\
& + T_b \sum_{j\in N\backslash\{1\}} \sum_{k\in N} q_j x_{1jk} \Bigg) + \Bigg(T_a \sum_{j\in N} \sum_{k\in N} t_{jk} x_{2jk} + T_b \sum_{j\in N\backslash\{1\}} \sum_{k\in N} q_j x_{2jk} \Bigg) \\
& + \ldots + \Bigg(T_a \sum_{j\in N} \sum_{k\in N} t_{jk} x_{(v-1)jk} + T_b \sum_{j\in N\backslash\{1\}} \sum_{k\in N} q_j x_{(v-1jk} \Bigg) \\
& - (v-1) \Bigg(T_a \sum_{j\in N} \sum_{k\in N} t_{jk} x_{vjk} + T_b \sum_{j\in N\backslash\{1\}} \sum_{k\in N} q_j x_{vjk} \Bigg) \Bigg\} \ldots
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\text{s.t.} & \left(T_a \sum_{j\in N} \sum_{k\in N} t_{jk} x_{ijk} + T_b \sum_{j\in N\backslash\{1\}} \sum_{k\in N\backslash\{1\}} q_j x_{ijk} \right) \geq \Bigg(T_a \sum_{j\in N} \sum_{k\in N} t_{jk} x_v jk \\
& + T_b \sum_{j\in N\backslash\{1\}} \sum_{k\in N\backslash\{1\}} q_j x_{vjk} \Bigg) \qquad \forall i \in I\backslash v \ldots
\end{aligned} \tag{2}
$$

$$\sum_{i\in I} \sum_{j\in N} x_{ijk} = 1 \qquad \forall k \in N\backslash\{1\} \tag{3}$$

$$\sum_{j\in N} \sum_{k\in N\backslash\{1\}} q_k x_{ijk} \leq c_i \qquad \forall i \in I \ldots \tag{4}$$

$$T_a \sum_{j\in N} \sum_{k\in N} t_{jk} x_{ijk} + T_b \sum_{j\in N\backslash\{1\}} \sum_{k\in N} q_j x_{ijk} \leq T_i \qquad \forall i \in I \ldots \tag{5}$$

$$\sum_{j\in N} x_i jk - \sum_{j\in N} x_{jk} = 0 \qquad \forall i \in I, k \in N \ldots \tag{6}$$

$$\sum_{k\in N\backslash\{1\}} x_{i1k} \leq 1 \qquad \forall i \in I \ldots \tag{7}$$

$$\sum_{j \in N \setminus \{1\}} x_{ij1} \leq 1 \qquad \forall i \in I \ldots \tag{8}$$

$$\sum_{i \in I} \sum_{j \in B} \sum_{k \in B} x_{ijk} \leq |B| - 1 \text{ for every nonempty subset } B \text{ of } \{2, \ldots, n\} \ldots \tag{9}$$

$$x_{ijk} \in \{0, 1\} \qquad \forall i \in I, j \in N, k \in N \text{ and } j \neq k \tag{10}$$

where:

for decision variables:

x_{ijk}= 1, vehicle i serves node j and k (customer); or

x_{ijk} = 0, vehicle i does not serve node j and k (customer);

for constants:

t_{jk}: the shortest distance between node j and node k

q_k: demand in weight for node k;

c_i: the maximum load capacity for vehicle i;

T_i: effective working time of vehicle i;

T_a: average travel time per kilometer for a vehicle;

T_b: average time spent on unloading at each node;

λ_1: weights for the shortest travel path;

λ_2: weights for the best load-balance between drivers;

v: total numbers of vehicles;

n: total number of nodes;

for each index:

$I = \{1, 2, \ldots, v\}$; set of vehicles;

N=$\{1, 2, \ldots, n\}$; set of nodes (N=1 stands for distribution center, others for customers).

The meaning of each equation is explained as follows:

Equation (1) states the objective of this model in finding the shortest travel path and the best vehicle working time balance simultaneously. The best vehicle working time balance means that the sum of the working time difference between each vehicle and the vehicle with the shortest working time would be the smallest. For example, there are three vehicles with working times of 20, 30 and 40 minutes respectively. The sum of the working time difference would be 30 (= (40 – 20) + (30 – 20) + (20 – 20)). According to equation (1), the additional task, finding the vehicle with the shortest working time, needs to be done. And thus, a constraint equation is added into the model (equation 2). Equation (2) selects the vehicle with the shortest working time (we pick truck ν). Because of this equation, the working time of other vehicles would be greater than or equal to the shortest working time of the selected vehicle in order to meet the requirement of equation (1), the objective function. Equation (3) represents that each node (customer) can be served by only one vehicle. Equation (4) represents the maximum load capacity constraint on vehicle i. Equation (5) represents the working time constraint for vehicle i. In other words, the vehicles have to finish the distribution jobs within the time limit. Equation (6) insures that vehicle routings are consecutive, i.e. when a vehicle has completed serving a certain customer, it leaves this customer and continues its schedule from this node. Equations (7) and (8) represent the fact that each vehicle can only make one round trip from the distribution center during an operational period of time. Equation (9) is put in place to avoid subtours. Equation (10) restricts the decision variable x_{ijk} to be a 0-1 integer.

Determining the values of λ_1 and λ_2 is an art, not a science. This research further assumes that the two objectives have equal weights. The number of vehicles (ν) is obtained by taking the total load capacity divided by the load capacity per vehicle. If the result is a decimal value, we round it to an integer. If there is no solution, one more vehicle is added and the process goes on until a solution can be found.

Characteristics of the model

There are two characteristics in the integer programming model:

(1) *NP-hard characteristic.* The decision variable (x_{ijk}) is either 0 or 1, so it becomes a 0-1 integer programming problem. It can also turn into a huge integer programming problem easily. Integer programming problems are NP-hard; and our formulation also exhibits the NP-hard characteristic. In other words, when the number of nodes increases, the calculation complexity for the problem will increase exponentially. In our research, a heuristic algorithm is developed to deal with the NP-hard characteristic. Test examples show that solutions obtained by the heuristic algorithm are good. This will be discussed in the next section.

(2) *Multi-objective characteristic.* There are two objectives in the model, so it is a multi-objective programming problem.

Heuristic algorithm design and validity evaluation

Generally, if the difference between the heuristic algorithm solution and the optimal one is low (5 per cent is a general upper limit of acceptance for evaluating the performance of an algorithm), then we may conclude that the heuristic algorithm performs well. Like the model mentioned previously, there are two objectives in this heuristic algorithm, viz, the shortest travel path and the best load-balance between drivers. A computer program is written in Visual Basic to implement this heuristic algorithm.

Heuristic algorithm design

There are nine steps in the heuristic algorithm.

Step 1. Calculate the minimum number of vehicles needed to meet the demand of each node of the network.

$$\nu = \left\lceil \frac{\sum_k q_k}{\sum_i C_i} \right\rceil \tag{11}$$

where:

q_k = demand for node k;

C_i = maximum load capacity for vehicle i;

ν = minimum number of vehicles needed. (If the result is a decimal value, round it to an integer.)

Equation (11) searches the minimum number of vehicles needed for an operational period of time to avoid resource waste.

Step 2. Calculate the shortest average working time per vehicle, namely AVT, to serve all of the nodes. The paper divides vehicle working time into two parts – time spent at the nodes and time spent traveling between all of the nodes. The shortest time for each part is calculated and summed up to get the shortest total working time. Then, the value of shortest total working time divided by the minimum number of vehicles needed is the AVT. Here is an example to demonstrate how to calculate AVT. In Figure 1, assume that a distribution center (DC) needs to serve four nodes. The number above each arc is the time spent traveling between two nodes. Assume that $\nu = 2$ from step 1 and unloading time is one for each node.

Then,

U_1 (= unloading time) = 1*4 = 4

U_2 (= sum of the 1st to νth shortest time from DC plus the sum of the shortest time for each node to other nodes) = (2 + 3) + (1 + 5 + 2 + 1) = 14

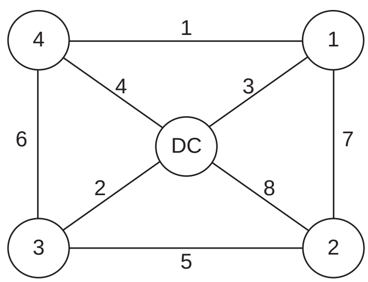

Figure 1.
An example to show how to calculate AVT

Hence,

$$\mathrm{AVT} = \frac{U_1 + U_2}{\nu} = \frac{4 + 14}{2} = 9 \quad (12)$$

If AVT is greater than the working time limit of any vehicle, then one more vehicle is added to serve the network.

Step 3. Calculate the saving value between two nodes by using equation (13).

$$s(i,j) = d(k,i) + d(k,j) + d(i,j) \quad (13)$$

In equation (13), $d(k,i)$ is the distance from node k to node i.

Figure 2 demonstrates the calculation done by equation (13).

The use of saving value can speed up the process of problem solving. It can also be added to the constraint easily, so it becomes a very practical problem solving method.

Step 4. Ranking of saving values. In arranging saving values ($s(i,j)$), if the same value occurs, rank the one with the smallest i value first and keep going in ascending order. If i value is also the same, then rank saving values by j value, in ascending order. For example, the saving values for s(2, 3), s(4, 7) and s(4, 10) are all five. The order for these three sets of saving values should be s(2, 3), s(4, 7) and s(4, 10).

Step 5. Based on the connecting rules, we need to find the set of service paths under the load limit for each vehicle and the working time limit AVT as calculated in step 2. The connecting rules are described as follows:

- The node with the biggest saving value should be considered first for connecting. However, only when all of the vehicle resource constraints (e.g. load limit and working time limit) are met can the node be connected.
- In connecting two paths, only the first node starting from the origin (or distribution center) or the last node on the returning path can be connected.

Step 6. Calculate vehicle working time for the v set of paths individually.

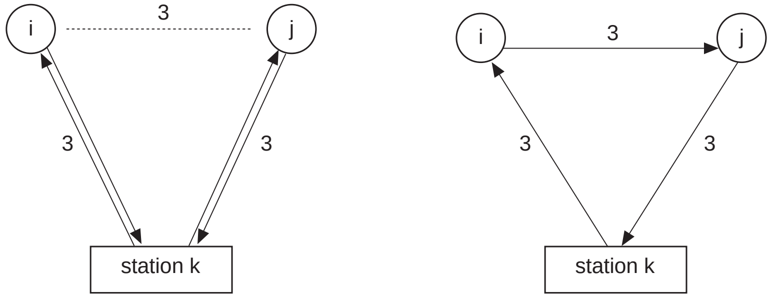

Figure 2.
Demonstration of saving value calculation

Step 7. Find out the vehicle with the shortest working time and assign the unserved node with the highest saving value to this vehicle route under vehicle resource constraints and connecting rules.

Step 8. Repeats steps 6 and 7 until all nodes are served.

Step 9. If no solution is found in step 8, add one more vehicle and start from step 2 again.

According to the above description, AVT is the shortest working time per vehicle to serve all of the nodes. In other words, if we use the optimal solution method to solve the problem, we may get AVT. For the proposed heuristic algorithm, in the first stage, the AVT time constraint is used to plan vehicle routes. In the second stage, the vehicle load limit constraint is used to arrange unscheduled nodes into planned vehicle routes in the first stage, and used as a mechanism to adjust working loads among vehicles.

Heuristic algorithm computer programming

According to the above calculation process, there are three factors which may affect the result of the proposed heuristic algorithm: first, the ranking of saving values and how these values are arranged; second, the value of AVT calculated in the first stage of vehicle routing planning, and third, the way the saving values are calculated. Different combinations of the three factors will produce different results. In our computer programs, we try different combinations to produce different results and the best result is picked as the solution. The explanation of these three factors is as follows:

(1) *Ranking of saving values* ($s(i,j)$). This research arranges saving values in two ways: one is the way described in step 4 of the heuristic algorithm. The other is that if equal saving values occur, arrange them by i value in descending order. If i value is also the same, then rank saving values by j value in descending order.

(2) *AVT calculation*. In our research, we use two different AVT values, namely AVT1(the value calculated in step 2) and AVT2(if AVT1 calculated in step 2 is a decimal value, we round it to an integer and this adjusted value of AVT1 is called AVT2), to find the final solution.

(3) *Saving value calculation*.

$$s(i,j) = [d(k,i) + d(k,j)] + W[d(i,j)] \quad (14)$$

Where W is the weight of the $d(i,j)$ objective.

Equation (13) is a special case of equation (14) when $W = 1$. In the computer programs, different W values are used to run the heuristic algorithm. The best value of these results will be the solution. We try different saving value calculation methodology in our programs: there are different W values; we arrange saving values in both ascending and descending order, and we use two AVT values to find the solution. So, for every fixed W value, calculation is run four times to find the best solution. If there are five W values, the calculation is run 20 times. Then, the best value is chosen from the 20 results as the solution. We know that the more W values entered, the longer the calculation times. Hence, computing time will also be longer. From our experience, if the range of W values is between 0.1 and 3, and the increase each time is 0.1, then the result will be much closer to the best solution. So, we apply these conditions in the heuristic algorithm.

Heuristic algorithm validity evaluation

In this section, 11 example runs are conducted to test the performance of the heuristic algorithm. These examples are based on a real logistics case. There are 15 nodes and they are spread widely in a region. The demand for each node and the distance between any two adjacent nodes are known. Therefore, we randomly disturb the demand and distance values within [–15 per cent, 15 per cent] range for each example.

To find out whether the three factors (ranking of saving values, AVT calculation method and saving value calculation method) mentioned previously will affect the heuristic algorithm result, two problem solving methods are used to find the results and to test the efficiency and validity of the heuristic algorithm. The first method is the optimal solution method, and the second one is the heuristic algorithm. We compare the results of these two methods and make research suggestions. A Pentium 100 PC with 24Meg Ram and PC Cplex version software are used to find the optimal solution for these test problems. Visual Basic (VB) computer language is used to code the programs for the heuristic algorithm.

This research evaluates the validity of the heuristic algorithm by analyzing computer calculating time, objective value, total travel distance and total vehicle working time difference. Table I is the comparison of the heuristic algorithm and the optimal method.

From Table II, the mean computer processing time of the heuristic algorithm is much lower than that of the optimal solution. Also, as shown by the standard deviation, the heuristic algorithm computer processing time is much more stable. There are no big fluctuations in processing time for different examples.

The comparison in computer calculating time in Table II, the total travel distance, and the ratio of vehicle working time difference to total working time of these two methods are used to prove that the heuristic algorithm as tested in the above 11 examples behaves well.

In these 11 examples, the difference between the total travel distance mean of the heuristic algorithm and the optimal solution is 0.735 per cent (Table I). Therefore, in terms of shortest travel distance, the result is acceptable (under 5 per cent difference condition).

The ratio of total vehicle working time difference to total working time tests how the heuristic algorithm performs in the driver load-balance objective. The mean of the ratios of these 11 examples is only 1.347 per cent apart from the optimal solution. So the result is satisfactory (under 5 per cent difference condition).

Table I. Comparison analysis between the result of the heuristic algorithm and the optimal solution (%)

Example no.	$Z_1 = \frac{u_1 - u_2}{u_2}$	$Z_2 = \frac{u_3 - u_4}{u_4}$	$Z_3 = u_5 - u_6$
1	5.479	2.740	1.818
2	0	0	0
3	2.440	–2.440	1.299
4	11.842	0	7.894
5	0	0	0
6	2.128	–2.128	2.410
7	4.878	7.692	–2.734
8	4.348	2.222	1.190
9	0	0	0
10	4.615	0	2.941
11	0	0	0
Mean	3.248	0.735	1.347
Variance	3.420	2.631	2.535

Notes:
Z_1: Ratio of two objective function value difference to objective function value obtained from the integer programming model
Z_2: Ratio of two total vehicle travel distance difference to total vehicle travel distance obtained from the integer programming model
Z_3: Difference of ratio of total vehicle working time difference to total working time
u_1, u_2: Objective function value obtained from heuristic algorithm and the optimal solution method respectively
u_3, u_4: Total vehicle travel distance obtained from heuristic algorithm and the optimal solution method respectively
u_5, u_6: Total vehicle working time difference to total working time ratio obtained from heuristic algorithm and the optimal solution method respectively

Table II. Computer calculating time comparison

Comparison item	Mean of computer processing time (second)	Standard deviation of computer processing time (second)
Optimal method	5643.909	4363.761
Heuristic algorithm	28.545	1.671

From the above comparison, it can be concluded that taking into consideration the two objectives, viz, the shortest travel distance and vehicle working time balance, the heuristic algorithm performs well because the results are within the acceptable range of 5 per cent.

Summary and recommendation

This research has brought driver load-balance factors into vehicle routing problems and developed a vehicle routing model by considering not only the shortest travel distance but also the best load-balance between drivers. To test the validity of the proposed heuristic algorithm, 11 test examples are conducted using the heuristic algorithm and the optimal solution method, and their results are compared. The summary of the research results are as follows:

- Because vehicle routing problems consist of NP-hard characteristics and are short-term planning problems, it will cost a lot of manpower and time to solve them by the optimal solution method. It is necessary to develop a convenient computer program. According to the 11 cases, the heuristic algorithm employed in this research produces good results. For the shortest travel distance, the difference of the two means is only 0.735 per cent. As for the best driver load-balance, the difference of the mean is 1.347 per cent as shown in Table I.
- Besides being precise, a good heuristic algorithm produces stable results whereas the optimal solution will not change significantly as the problem changes. This research looks into different factors that may affect the results of the heuristic algorithm, and we chose the best values from the results of different combinations as the output to meet stability in the problem solving process. Since the differences in standard deviations are stable (between 2.535 and 3.420), it can be concluded that the performance of the heuristic algorithm is stable. We can at least say that the performance of the heuristic algorithm is good in these examples built on real logistics cases.
- By changing the ranking method of saving value, the saving value calculation method and the AVT value, this research chooses the best value from the results of different combinations as the output to meet stability. However, computer calculating time is also increased. If a mathematical formula can be designed to find the best values of these three factors, then computer calculating time can be reduced drastically.
- For integer planning models, future researchers might want to aim to reduce the number of decision variables and constraints in order to cut down computer calculating time and to improve the practicality of the optimal solution method.

In conclusion, the main contribution of our research is to help improve the fairness among employees or drivers by balancing their workload. Workload was formulated as vehicle routing problems with load-balancing factor. Based on this formulation, we proposed a heuristic algorithm. In this paper we also prove that the proposed algorithm provides precise and stable solutions.

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