A Comparative Analysis of Heuristic Methods for Facility Location and Allocation of Buses to Facilities in Urban Road Transportation Systems

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Abstract

The city buses operating in the Urban Road Transportation Systems (URTS) cover various non-revenue generating distances without carrying passengers. One such distance travelled from a facility in the early morning to starting point of first trip and ending point of last trip back to the facility in the late evening is the 'dead kilometers or mileage' (DK). Since the mileage per unit of the fuel varies, minimizing DK cost (DKC) associated with allocation of city buses to facility (ACBF) problem is an ideal objective than minimizing DK. This DKC is directly affected by the location of the facilities and assignment of each of the buses to a specific facility. Due to continuous growth of any metro-city and commuters of city-buses, the number of city-buses need to be increased. Further, due to environmental and logistic reasons, a few existing facilities need to be closed. Due to this there is a need to open new facilities. For closing the existing facility(s), a salvage cost is incurred and for opening new facility(s), fixed cost is incurred. So, in any URTS, there is facility location (FL) problem for opening and/or closing facility(s).

Further, FL and ACBF problems are inseparable as DKC is the common cost affecting the decisions associated with each of these decision problems. So, this study considers the integrated decision problem on FL and ACBF (FL-ACBF). Accordingly, the focus of this research is to (a) identify the best-known heuristics from literature for minimizing simultaneously fixed cost, salvage cost, and DKC for FL-ACBF; and (b) evaluate empirically the performance of identified heuristics for selecting efficient heuristic(s).

Keywords
Urban Road Transportation System, Location of Facility, Allocation of City Buses to Facility, Dead Kilometer Cost, Fixed Cost, Salvage Cost, Heuristics, Performance Evaluation

1. Introduction
The transport sector in India is largely controlled by the State Road Transport Undertakings (SRTUs) through their provision of inter-state, inter-city, and some intra-city services in selected cities. A few metropolitan cities have exclusive city transport corporations formed for city bus operations comprising the Urban Road Transportation System (URTS). Every Indian URTS (I-URTS) is a metropolitan/municipal-based SRTU.

A recent amendment of the National Urban Transportation Policy (NUTP) in 2014 by the Indian government prioritizes public transport and allows its citizens "safe, affordable, quick, comfortable, reliable and sustainable access" (MoUD 2014). This also leads to a government mandate to put a price ceiling on bus fares for equitable transportation service. Despite high user dependence on city bus systems, going by the financial performances of each of the SRTUs in India (MoRTH, 2017), it is observed that almost every URTS in India is facing huge losses in operating buses. Due to this, the I-URTS find it challenging to raise their revenue sufficient enough to cover their cost of city bus operations (CCBOs) (Singh 2012). Hence, these systems require strategic interventions to minimize the CCBOs without changing the existing fare level. With this premise, this study aims to identify and address one such decision problem i.e., the Facility Location (FL) integrated with the allocation of city buses to facility (ACBF) problem (FL-ACBF).

The objective of the ACBF problem is to allocate the given number of buses to the available number of facilities. Based on a quick analysis of literature, it is observed that the ACBF problem considers two different broad objectives: one is minimizing the dead kilometers (DK), and the other is minimizing the DK cost. The city buses in I-URTS cover various non-revenue generating distances i.e., without carrying passengers. One such non-revenue generating distance is the Dead Kilometers (DK) (Mathirajan et al. 2010). However, the decision on the ACBF is not independent of the decision on location of facilities (FL) (Mathirajan et al. 2021). This is because the location of facilities affects DK. Although FL impacts DK, it is limited depending on the availability and cost of land (Tirachini and Hensher 2011). In metropolitan cities where land cost is high, and space is limited, bus facilities need to be developed in the city's outskirts which may increase the DK traversed by the bus. Hence, FL and ACBF are inseparable problems.

In every URTS, the strategic decision problem on FL-ACBF arises whenever the existing facilities are not sufficient due to increasing the number of buses and/or due to closing the existing facility(s) and opening new facility(s). Some of the reasons for this decision problem are, (i) as the city size is continuously increasing due to people migrating for jobs, the public communication facilities become essential, and the number of existing buses needs to increase and in turn the existing number of facilities needs to increase, and (ii) as a city expands, the existing facilities fall in the inner part of the city and this might create various menace to the public and due to this the existing facility(s) need to be closed and because of this as well as to maintain the existing number of buses, the URTS need to introduce new facility(s). In the case of closing the existing facility(s), the URTS could sell off the land associated with closing facility(s), or could use it to attract other business opportunities for the URTS – this would yield a salvage cost to URTS. In the case of opening new facility(s), fixed cost associated with opening new facility(s) is incurred by the URTS. With this, simultaneously minimizing the fixed cost, salvage cost and dead-kilometer cost would help the URTS to minimize the CCBOs.

The paper is organized as follows: In Section 2, we discuss the problem description of the FL-ACBF briefly. Section 3 presents a review of the existing literature on the problem. Section 4 discusses the methodologies proposed for the FL-ACBF problem towards minimizing the cost of city bus operations. Section 5 briefly presents the required details for the performance analysis of the proposed methodologies. The analysis of the results with discussions is presented in Section 6. Finally, we conclude the paper in the last section.

2. Problem Description

Let N be the number of buses available for optimal/efficient allocation to M number of facilities. Each facility has a facility capacity (FC_j) for j = 1,2….M facilities. The values of the additional parameters: Dead Kilometers DK_{ij} if bus 'i' (i = 1,2…. N buses) is allocated to facility 'j' (j = 1,2….M facilities), Mileage/Kilometers per liter (kpl_i) of fuel for each bus 'i', and the price of fuel (P) are known. With these given data, the dead kilometer cost (DKC_{ij}) for each bus 'i' can be computed, w.r.t. to the each of the facility j as its choice for allocation, as follows:

$$DKC_{ij} = DK_{ij} \times \frac{P}{kpl_i}$$

Similarly, for calculating the fixed cost for opening a new facility (FCOF), the values of FCj (j = 1,2….M facilities) is known.

$$FCOF_j = FC_j \times Z_j$$

Where, Z_j = 1 if facility 'j' is new and opened.

Likewise, for calculating the salvage cost for closing an existing facility (SVCF), the values of SCj (j = 1,2….M facilities) is known. Hence,

$$SVCF_j = SC_j \times Y_j$$

Where, Y_j = 1 if depot j is existing and closed.

Considering the above data, applicable for every facility 'j' for each of the buses 'i', the objective of the FL-ACBF problem is to allocate the given N number of buses to the available M number of facilities by minimizing the total DKC, FCOF and the SVCF.

3. Literature Review

This section discusses the studies which treat the location of facilities (FL) and the allocation of city buses to facilities (ACBF) in an integrated manner. Prior to this, a brief review on facility location-allocation (FLA) is given in the following section.

3.1 A Review on Facility Location – Allocation (FL-A) in General

The decisions on facility location are very critical as the ramifications have a long-lasting and profound impact on the tactical and operational decisions in any organization. Most of the research done before 1970 focused primarily on manufacturing facilities. Thereafter, the inclusion of service sector to the facility location problem was discussed.

Farahani et al. (2013) examined multi-objective extensions of the basic facility location model and observed that the majority of urban service sector applications focused on the joint decision of facility location-allocation (FLA) problem rather than pure locational decisions. The determination of the optimal number, location, and size of facilities is known as the facility location – allocation (FL-A) problem. It belongs to one of the oldest classes of decision problems in Management Science (Balinski 1961). FL-A decisions require huge capital investment and depend upon several tangible and intangible factors. They result in long-term impediments on the production and distribution operations of an organizations. Furthermore, there are many extensions to the FL-A problem. This study aligns itself with one such extension i.e., the capacitated FL-A model for a bus-facility system since all the bus facilities have certain capacity constraints. Moreover, it becomes difficult for buses to enter or leave the facility if too many buses are allocated to the same facility (Chen et al. 2021).

3.2 A Review on Facility Location – Allocation of City Buses to Facilities (FL-ACBF)

The studies by Maze et al. (1981) and Maze et al. (1982) are one of the earliest applications of the FL-ACBF problem. However, due to the unavailability of efficient computational software in those days, the authors had to drop the fixed/binary (0-1) variable related to the opening or not opening of a facility. Further, since the authors did not include any salvage value for closing an existing facility, the model did not result in the opening of a new facility due to the minimum cost objective function.

Uyeno and Willoughby (1995) addressed the immediate limitation of the above-mentioned research studies by proposing a Mixed Integer Linear Programming (MILP) model and a (0-1) MILP model, respectively. The objective of their study was to minimize the total costs, which included the total dead kilometer cost (DKC), fixed cost of opening a facility (FCOF), and salvage cost to close an existing facility (SVCF). However, the immediate limitation of their study was also recognized as a managerial inconvenience by the scheduling personnel. This was because the buses on a given route were split between the facilities. Willoughby and Uyeno (2001) later developed a heuristic algorithm to address this limitation. They presented an optimal solution allowing split routes, i.e., the assigned buses for a specific route were from different facilities.

Hsu et al. (2021) proposed an augmented (0-1) Integer Linear Programming (ILP) model to address the problem of the facility, charging, and maintenance-related facilities' location for the comprehensive deployment of a mixed-bus system. As the problem turned out to be NP-hard, the authors proposed a decomposition-based two-stage heuristic algorithm to boost computational efficiency. Their sensitivity and scenario analyses indicated that replacing larger facilities with smaller facilities shortened the deadhead mileage, further reducing operating costs. Mathirajan et al. (2021) developed a greedy heuristic algorithm for approaching the FL-ACBF problem in an integrated manner, bringing down the overall CCBOs. The heuristic addressed three costs: the total DKC, FCOF, and SVCF. Furthermore, to reduce the complexity of decision-making, in another study, Mathirajan et al. (2021) incorporated this heuristic algorithm in a Cloud-based Decision Support System (C-DSS) for transport analytics in the I-URTS. Their results indicated that the C-DSS performed efficiently with a loss of optimality between 0-4 percent approximately. The authors proposed that the user-friendly web interface of the C-DSS would provide more flexibility in the information exchange operations in the context of India.

The above briefly reviewed literature on FL-ACBF research is summarized in Table 1. From Table 1, it is observed that a scant treatment has been given to India for addressing the FL-ACBF problem, although there are several studies looking at the ACBF problem separately in the Indian context. This research gap is addressed in this study.

4. Proposed Methodologies for FL-ACBF Problem

The FL-ACBF problem can be viewed as a ***special type*** of a transportation problem (Vasudevan et al. 1993; Mathirajan et al. 2010). Typically, large-scale transportation problems are solved using efficient heuristic methods, which provide near-optimal solutions. Over 100 heuristic methods have been discussed in existing literature, with many researchers incorporating the total opportunity cost matrix (TOCM) proposed by Kirca and Satir (1990) alongside the transportation cost matrix (TCM). However, almost every published research paper does not have a rigorous computational evaluation process to measure the effectiveness of these heuristic methods. A recent study by Mathirajan et al. (2022) proposed various new heuristic methods and considered various existing heuristics that have been empirically and statistically found to be better-performing followed by extensive computational evaluations. Keeping this as a base research paper, the following 12 heuristic methods: top 10 performing heuristic methods according to the study by Mathirajan et al. (2022) and 2 well-known existing heuristic methods with demonstrated efficacy in the literature – are considered for application in the FL-ACBF problem and to assess their relative performances.

RCWMCAM-TCM: Row-Column Weighted Minimum-Cost-Allocation Method applied on Total Cost Matrix (TCM)

RCWMCAM-TOCM: RCWMCAM applied on Total Opportunity Cost Matrix (TOCM)

WUPCM2-TCM: Weighted-Unit-Penalty-Cost Method-2 applied on TCM

WUPCM2-TOCM: WUPCM2 applied on TOCM

RCMCAM-TCM: Row-Column Minimum-Cost-Allocation Method applied on Total Cost Matrix (TCM)

RCMCAM-TOCM: RCMCAM applied on Total Opportunity Cost Matrix (TOCM)

RAM-TCM: Russell's Approximation Method applied on TCM

RAM-TOCM: RAM applied on TOCM

MDM- TCM: Maximum Demand Method applied on TCM

MDM- TOCM: MDM applied on TOCM

VAM- TCM: Vogel's Approximation Method applied on TCM

VAM- TOCM: VAM applied on TOCM

The above 12 heuristic methods are coded in Python. To verify their correct implementation, the Python implementation of each of these 12 heuristic methods is applied to a numerical problem and the obtained solution is validated with the solution obtained manually for each of the heuristics. Due to the brevity of the paper length issue, these details are not presented in the paper.

5. Performance Evaluation of the Heuristic Algorithms, considered, for FL-ACBF Problem

There are three components involved in any performance evaluation and they are numerical example, bench mark procedure(s), and performance measure(s). The details of these components involved in this study are given as follows:
Numerical Example: The numerical example developed to reflect the FL-ACBF problem in Mathirajan et al. (2021) has been used in this study. In the example, there are 3 existing facilities and 4 candidate locations for opening new facilities. The total number of buses is 20. Out of the existing facilities, the management wishes to close 1 facility and out of the potential facilities, the management wishes to open 2 of them. A Python code is written for randomly generating all possible combinations of opening and closing the facilities, considering each of the 12 heuristic algorithms.
Benchmark Procedure: For absolute performance evaluation of the 12 heuristic algorithms considered for the FL-ACBF problem, the (0-1) MILP model proposed in Mathirajan et al. (2021) is considered as bench mark procedure.

Performance Measure: The performance analysis of the 12 heuristic algorithms considered in this study is carried out using the performance measure: average relative percentage deviation (ARPD), which is computed using the following equation:

$\mathrm{ARPD_i} = \sum_{i=1}^{12} \mathrm{RPD_i}/12$ (1)

$$RPD_i = \frac{Total\ cost\ yielded\ by\ heuristic\ algorithm_i - Optimal\ cost\ yielded\ by\ the\ (0-1) ILP\ Model}{Optimal\ cost} \times 100 \quad (2)$$

Table 1. A summary on the existing literatures on the FL-ACBF problem

Authors	Year	Country	Problem Type (D/S)	Objective is to Minimize				Location of Facility (O/C/O&C)	Methodology	Type of Model	Source of Data
				DK	DKC	FCOF	SVCF				
Maze et al.	1981	-	D		✓	✓		O	MM	(0-1) MILP	HE
Maze et al.	1983	US	D		✓	✓		O	MM & HA	(0-1) MILP	Case Data
Uyeno and Willoughby	1995	Canada	D		✓	✓	✓	O&C	MM	(0-1) MILP	Case Data
Willoughby and Uyeno	2001	Canada	D		✓	✓	✓	O&C	HA	2 step HA	Case Data
Hsu et al.	2021	Taiwan	D		✓	✓	✓	O&C	MM & HA	ILP; GHA	Case Data
Mathirajan et al.	2021	India	D		✓	✓	✓	O&C	MM & HA	MILP; GHA	ED

Meaning of Abbreviations used: D – Deterministic, S – Stochastic, O – Opening, C – Closing, MM – Mathematical Model, DKC – Dead Kilometer Cost, FCOF – Fixed Cost of Opening Facility, SVCF – Salvage Value of Closing Facility, HA – Heuristic Algorithm, GHA – Greedy HA, HE – Hypothetical Example, LP – Linear Programming, (0-1) MILP – (0-1) Mixed Integer LP, ED – Experimental Design

6. Results and Discussions

Considering the number of facilities to be opened from the given feasible number of facilities and the number of given existing facilities to be closed from the given feasible existing facilities for closing, 12 combinations of FL-ACBF problems are generated from the given numerical example. Each of these combinations result in one FL-ACBF with specific set of existing facilities, opening new facilities, and closing a facility. This becomes simply an ACBF problem. With this we will have 12 set of ACBF problems. Each of these 12 problems is solved using each of the 12 heuristic algorithms considered in this study and the obtained total cost (in thousands of INR) is presented in Table 2. The optimal solution obtained (that is, total cost in thousands of INR) using the (0-1) mixed integer linear programing (MILP) model (presented in Mathirajan, et al. (2021)), is presented in last column of Table 2. Using equation (2) and the results presented in Table 2, the relative percentage deviation (RPD) is computed for each of the 12 heuristic methods w.r.t the optimal solution and the same is presented in Table 3. From the RPD scores (Table 3), the average relative percentage deviation (ARPD) was obtained using equation (1) as and the same is presented in Figure 1. From the analysis of the Table 2 and Figure 1, it is observed that

- out of the 12 combinations for the one numerical example considered, the best combination is opening facilities: 5 and 7 and closing facility: 3. All the heuristic methods yield the lowest total cost for this combination (Table 2).
- The results presented in Table 2 and Table 3 indicate that each of the 12 heuristic methods are almost giving near to optimal solution. But this observation cannot be generalized as only one the numerical example is considered here and the problem considered is very small.
- the recent study, considering the traditional transportation problem, by Mathirajan et al. (2022) empirically and statistically proved that (a) the 2 variants of the newly proposed heuristic method, RCWMCAM (that is RCWMCAM applied on TCM and RCWMCAM applied on TOCM) are outperforming all the other 32 heuristic methods considered in their study, and (b) existing heuristic methods: MDM and RAM are relatively performing well in comparison with other existing heuristic methods in the literature. However, these findings/observations are NOT completely matching with the results presented in Figure 1. This could be due to the fact that the problem considered in this study: FL-ACBD is a special type of transportation problem and not the traditional transportation problem.
- it appears that both the variants of RAM (that is RAM applied on TCM and RAM applied on TOCM) are performing well and yielding similar results (Figure 1). This is not consistent with the earlier findings where RCWMCAM was outperforming the other heuristics (Mathirajan et al. 2022).
- out of 12 heuristic algorithms considered in the study for performance evaluation, the existing heuristic: VAM yielded next better results (Figure 1).

All the above observations may/may not be true for large-scale problems and may not be true when we compare other better performing heuristic methods for the traditional transportation problem reported in the literature. So, the present study has limitations regarding (a) absence of an experimental design to use more problem configurations, (b) considered only 12 heuristic methods from the recent study by Mathirajan et al. (2022) and (c) the type of performance measure used.

Table 2. **Total Cost** (in thousands of INR) **obtained** w.r.t. each of 12 Heuristic Algorithms as well as (0-1) MILP Model and w.r.t. each of possible combination of opening and closing depot of the numerical example considered

Sl. No.	Combinations (Opening Depots, Closing Depot)	RCWMCAM-TCM	RCWMCAM-TOCM	WUPCM2-TCM	WUPCM2-TOCM	RCMCAM-TCM	RCMCAM-TOCM	RAM-TCM	RAM-TOCM	MDM-TCM	MDM-TOCM	VAM-TCM	VAM-TOCM	Optimal Solution
1	(4,5,1)	97.4	97.3	97.2	97.3	97.3	97.3	97.2	97.2	97.6	97.6	97.2	97.2	97.1
2	(4,5,3)	77.2	77.3	77.2	77.3	77.2	77.2	77.2	77.2	77.6	77.6	77.2	77.2	77.1
3	(4,6,1)	147.4	147.4	147.5	147.4	147.3	147.4	147.3	147.3	147.9	147.9	147.4	147.2	147.2
4	(4,6,3)	127.3	127.3	127.5	127.3	127.4	127.3	127.3	127.3	127.9	127.9	127.3	127.3	127.2
5	(4,7,1)	117.4	117.4	117.3	117.4	117.4	117.4	117.2	117.3	117.6	117.5	117.4	117.4	117.2
6	(4,7,3)	97.5	97.4	97.4	97.3	97.4	97.4	97.3	97.3	97.6	97.5	97.4	97.4	97.2
7	(5,6,1)	72.2	72.3	72.5	72.3	72.3	72.3	72.2	72.2	72.5	72.5	72.2	72.2	72.1
8	(5,6,3)	52.2	52.2	52.5	52.2	52.3	52.2	52.2	52.2	52.5	52.5	52.2	52.2	52.1
9	(5,7,1)	42.2	42.3	42.2	42.3	42.3	42.3	42.2	42.2	42.5	42.4	42.2	42.2	42.1
10	**(5,7,3)**	**22.2**	**22.2**	**22.3**	**22.3**	**22.3**	**22.2**	**22.2**	**22.2**	**22.5**	**22.4**	**22.2**	**22.2**	**22.1**
11	(6,7,1)	92.3	92.3	92.3	92.3	92.4	92.3	92.2	92.2	92.7	92.5	92.3	92.3	92.2
12	(6,7,3)	72.3	72.4	72.4	72.4	72.4	72.4	72.3	72.3	72.7	72.5	72.3	72.3	72.1

Note: Blue numbers correspond to opening new facilities whereas, red numbers correspond to closing the existing facilities

Table 3. RPD scores obtained by the proposed heuristic algorithms w.r.t. optimal solution

Sl. No.	Combinations (Opening Depots, Closing Depot)	RCWMCAM-TCM	RCWMCAM-TOCM	WUPCM2-TCM	WUPCM2-TOCM	RCMCAM-TCM	RCMCAM-TOCM	RAM-TCM	RAM-TOCM	MDM-TCM	MDM-TOCM	VAM-TCM	VAM-TOCM
1	(4,5,1)	0.19	0.10	0.06	0.10	0.10	0.10	0.04	0.04	0.41	0.42	0.05	0.01
2	(4,5,3)	0.08	0.18	0.12	0.18	0.12	0.13	0.12	0.07	0.56	0.57	0.02	0.08
3	(4,6,1)	0.09	0.11	0.16	0.11	0.08	0.11	0.04	0.02	0.43	0.43	0.09	0.02
4	(4,6,3)	0.05	0.11	0.24	0.11	0.14	0.11	0.08	0.07	0.52	0.53	0.05	0.05
5	(4,7,1)	0.18	0.13	0.05	0.13	0.14	0.13	0.01	0.05	0.31	0.29	0.18	0.17
6	(4,7,3)	0.26	0.19	0.18	0.14	0.23	0.20	0.06	0.07	0.36	0.34	0.19	0.22
7	(5,6,1)	0.04	0.16	0.40	0.16	0.20	0.16	0.05	0.05	0.50	0.44	0.04	0.04
8	(5,6,3)	0.14	0.18	0.65	0.18	0.38	0.18	0.12	0.12	0.75	0.65	0.16	0.17
9	(5,7,1)	0.06	0.36	0.25	0.36	0.43	0.36	0.06	0.08	0.92	0.60	0.06	0.10
10	(5,7,3)	0.28	0.48	0.98	0.60	0.72	0.52	0.30	0.30	1.79	1.18	0.30	0.28
11	(6,7,1)	0.09	0.16	0.14	0.14	0.25	0.14	0.03	0.01	0.51	0.35	0.09	0.09
12	(6,7,3)	0.13	0.26	0.25	0.26	0.27	0.26	0.17	0.19	0.66	0.46	0.12	0.17

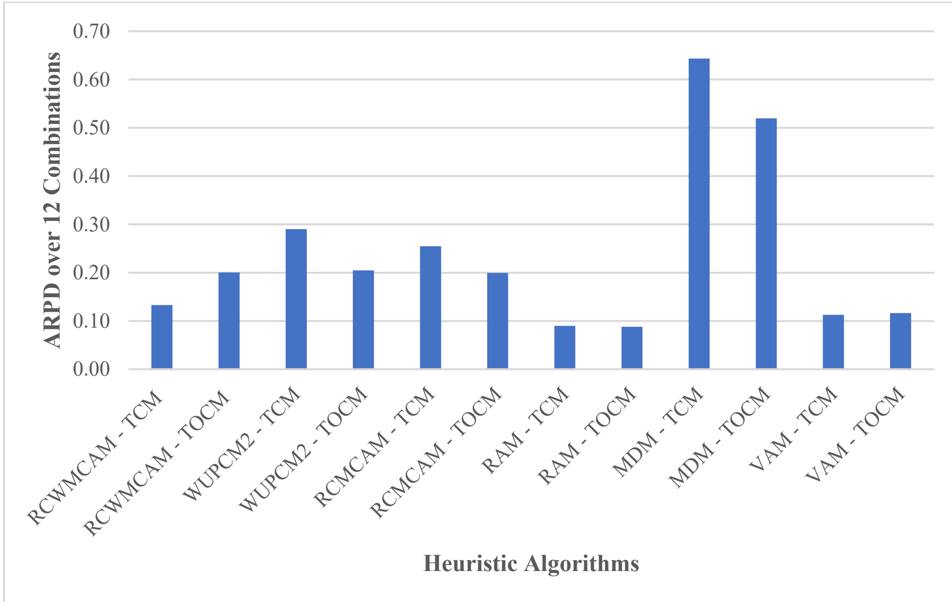

Figure 1. Average performance of the heuristics w.r.t the optimal solution

7. Conclusions

This study considers a new objective for the decision problem: FL – ACBF of I-URTS to minimize the CCBOs. As this problem can be viewed as a special type of transportation problem, the best-known heuristic methods reported in the literature for the traditional transportation problem are considered to apply to the FL – ACBF problem and to understand the status of these heuristic methods. For this research objective, a numerical example is considered. The analysis of the results indicated that the best performing heuristic methods reported in the recent studies, for the traditional transportation problem, are not necessarily performing as best when we applied these for the special case of the transportation problem such as FL – ACBF problem!! Further, the performance analysis indicated that both the variants of existing heuristic method: RAM outperformed all the other heuristics for the FL – ACBF problem. These inferences motivate us to address all the listed limitations of the present study as immediate future activity.

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Biographies

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